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The Honorable Kristina Johnson
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Senior Vice President, Education, PBS

The Honorable Anthony Wilder Miller
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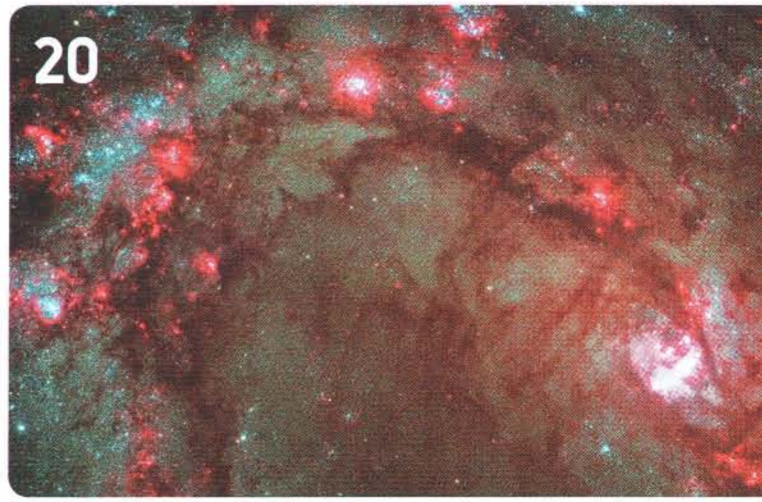

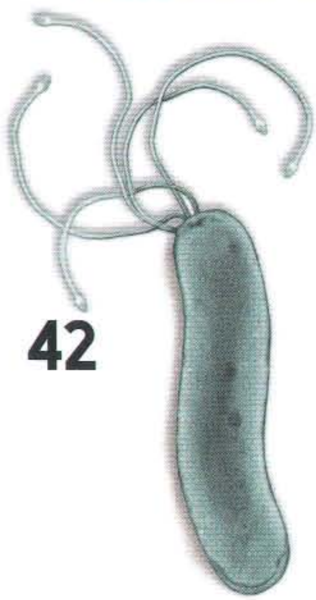

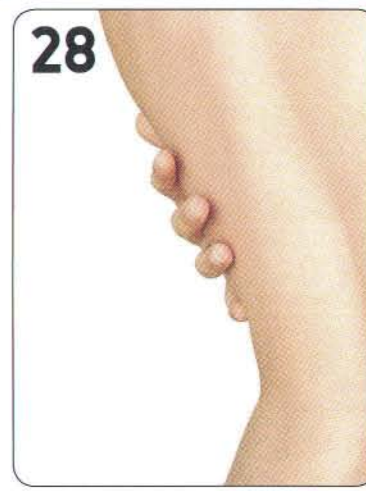

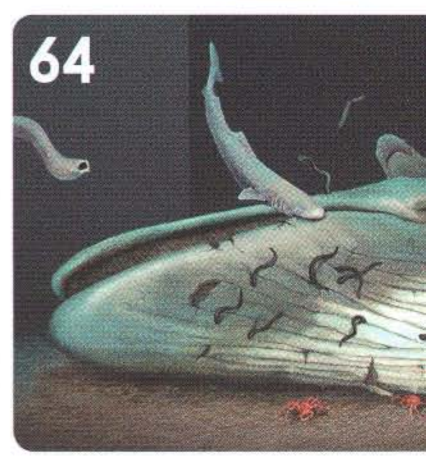

ON THE COVER

Human beings are the only primate species bedecked in mostly naked skin. How and why did we lose so much of our hair?
Image by Anthony Marsland, Getty Images.

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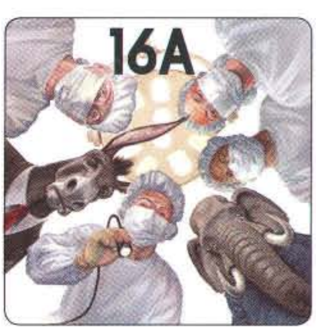

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The Internet at 40

Four decades ago the Defense Department connected computer nodes at four universities—a historic linkup that would evolve into the Internet. One defense agency marked the 40th anniversary with a social-networking balloon hunt.

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KUWAIT PRIZE 2010
Invitation for Nominations

The **Kuwait Foundation for the Advancement of Sciences (KFAS)** institutionalized the **KUWAIT Prize** to recognize distinguished accomplishments in the arts, humanities and sciences. The Prizes are awarded annually in the following categories:

A. Basic Sciences
B. Applied Sciences
C. Economics and Social Sciences
D. Arts and Literature
E. Arabic and Islamic Scientific Heritage

The Prizes for 2010 will be awarded in the following fields:

1. Basic Sciences	: Chemistry
2. Applied Sciences	: Biomedical Technology
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4. Arts and Literature	: Studies in Al-Jahili Poetry
5. Arabic and Islamic Scientific Heritage	: Architecture

Foreground and **Conditions** of the Prize:

1. Two prizes are awarded in each category:
   * A Prize to recognize the distinguished scientific research of a Kuwaiti citizen, and,
   *A Prize to recognize the distinguished scientific research of an Arab citizen.
2. The candidate should not have been awarded a Prize for the submitted work by any other institution.
3. Nominations for these Prizes are accepted from individuals, academic and scientific centers, learned societies, past recipients of the Prize, and peers of the nominees. No nominations are accepted from political entities.
4. The scientific research submitted must have been published during the last ten years.
5. Each Prize consists of a cash sum of K.D. 30,000/- (approx. U.S.$100,000/-), a Gold medal, a KFAS Shield and a Certificate of Recognition.
6. Nominators must clearly indicate the distinguished work that qualifies their candidate for consideration.
7. The results of KFAS decision regarding selection of winners are final.
8. The documents submitted for nominations will not be returned regardless of the outcome of the decision.
9. Each winner is expected to deliver a lecture concerning the contribution for which he was awarded the Prize.

Inquiries concerning the KUWAIT PRIZE and nominations including complete curriculum vitae and updated lists of publications by the candidate with **four copies** of each of the published papers should be received before **31/10/2010** and addressed to:

The Director General

The Kuwait Foundation for the Advancement of Sciences - P.O. Box: 25263, Safat - 13113, Kuwait.
Tel: (+965) 22429780 / Fax: 22403891 / E-Mail: prize@kfas.org.kw

Continuum of Change

Darwin doubters have some-times questioned evolutionary theory by asserting that no "missing link" exists between humans and other primates. But the fossil record shows that there was no instant leap to humanity: rather our species' physical hallmarks appeared gradually over the past several million years. "Humans did not suddenly come into existence, but we share features with many other [species]," John G. Fleagle, an anatomist at Stony Brook University, has said. Fingernails evolved 54 million years ago (mya) and the opposable thumb 25 mya, for instance. The pelvis shape needed for walking upright as well as the knee appeared more than 3.5 mya, and the foot arch arose around 1.8 mya. Although skull construction was set around 35 mya, brains only ballooned in size between 2 and 1 mya, and the chin dates from around 200,000 years ago. With apologies to Shakespeare's Hamlet: what a patchwork is a man.

One feature that visibly separates us from most other mammals is our lack of fur. As Nina G. Jablonski explains in our cover story, "The Naked Truth," beginning on page 28, the transition of hirsute to hairless helped to set the stage for the emergence of large brains and symbolic thought. The appearance of bare skin was one of a suite of adaptations that allowed our ancestors to thrive on the savanna as grasslands expanded in Africa starting about three million years ago.

Our forebears abandoned their easier foraging habits, traveling longer distances through a tropical landscape to acquire sufficient food to survive. Adding meat to their diets meant more calories, but finding prey also took more work. Their activity level increased and with it their need to dissipate body heat to avoid tissue damage. By 1.6 mya, protohumans had long legs for sustained walking and running. Along with that trait came naked skin and a large number of eccrine sweat glands, which produce moisture that removes body heat through evaporative cooling. The hairs on our head also help to combat overheating, by shielding our big brain from direct sun.

Although the board of editors didn't plan it this way, many of the other feature articles in this issue also examine changes over time. The connection is most direct in "The Art of Bacterial Warfare," by B. Brett Finlay (page 42), which describes the ancient battle between infectious agents and their human hosts. But other articles also describe "evolution" in various areas.

Whereas Finlay's article focuses on inner space, for instance, "Cloudy with a Chance of Stars," by Erick T. Young (page 20), looks at outer: how stars arise and change over time, a seemingly simple question that has long puzzled astronomers. "The Prolific Afterlife of Whales," by Crispin T. S. Little (page 64), explores how sunken whale carcasses today—and dinosaurs millions of years ago—support a series of ecosystem oases on the seafloor. Even "Better Mileage Now," by Ben Knight (page 36), looks at how internal-combustion engines are changing, creating improved performance. By explaining such advances, SCIENTIFIC AMERICAN strives to fulfill its mission of demystifying a changing world. ■

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The Oil Crisis ▪ Biotech Food ▪ Brain Pills

OCTOBER 2009

> **"Genetic engineering is unlikely to play a significant role in increasing food production in the foreseeable future."**
> —*Edith Borie* KARLSRUHE, GERMANY

End or No End?

In "Squeezing More Oil from the Ground," Leonardo Maugeri, director of strategies and development of an international oil company, expresses the conventional view of his profession, assuming a world of near-infinite oil resources to be produced under market forces. Maugeri is particularly dismissive of our *Scientific American* article "The End of Cheap Oil" [March 1998]. It is difficult to find fault with at least its title, considering that the average price of oil over the preceding 10 years was $28 a barrel but rose to $45 over the ensuing decade to reach a peak of almost $150 in 2008.

Given the central place of oil-based energy in the modern world, it is critically important that governments should base their policies on realistic depletion profiles, despite ambiguous definitions and lax reporting practices. Decline typically commences at about midpoint of depletion, as already exemplified in more than 50 countries. World discovery peaked in the 1960s and must deliver a corresponding peak of production. A debate rages as to the precise date of peak but misses the point when what matters is the vision of the long decline on the other side of it.

Colin Campbell
Founder, Association for the Study of Peak Oil and Gas
Jean Laherrère
President, ASPO France

MAUGERI REPLIES: *It seems to me that the conventional view about oil has become precisely the one proposed by Campbell and Laherrère: that the world is heading toward peak production. In my article, I never say that oil is bound to last forever. Instead I warn against those who affirm to know when its production will peak, because no one can calculate the future derivate of an unknown stock. This is simply a nonscientific approach to the issue, as proved by the repeated mistakes in their calculations about the "peak" period. In fact, we still don't know that much about the subsurface inner secrets, nor do we know the exact oil endowment of our planet.*

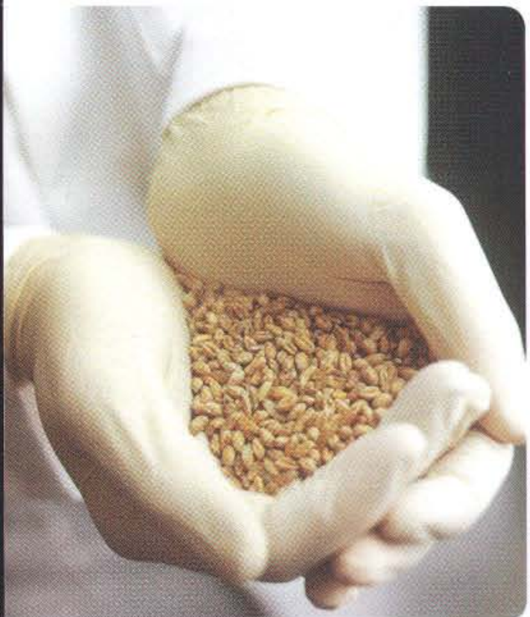
As to the issue of cheap oil, we should agree on the meaning of "cheap." What appears expensive today could be much cheaper in the future, thanks to the advancement of technology. The negative psychology created by unjustified alarmism about peak oil continues to introduce instability and volatility in the market, harming any concept of sustainable development because uncertainty could determine a sort of "energy investment paralysis."

Feed the World

The agricultural industry may see biotechnology as an important part of farming's future, as four biotech executives say in "Biotech's Plans to Sustain Agriculture." But the evidence is not very strong for this very biased viewpoint. The opposite is described very well in the study "Failure to Yield," by the Union of Concerned Scientists (www.ucsusa.org/food_and_agriculture). That the problem is one of distribution more than production is highlighted by the fact that Americans throw away enough usable food to feed all the hungry in Africa. And although DNA-marker-assisted breeding seems to be help-

ful to increase yields, gene insertion seems to be much less useful.

"Failure to Yield" concluded that genetically engineering herbicide-tolerant soybeans and herbicide-tolerant corn have not increased yields. Insect-resistant corn, meanwhile, has improved yields only mar-



CONTROVERSIES PERSIST on transgenic crops' environmental and economic effects.

ginally. The increase in yields for both crops over the past 13 years, the report found, was largely attributable to traditional breeding or improvements in agricultural practices.

Biotechnology companies maintain that genetic engineering is essential to boost agricultural productivity. The UCS report debunks that claim, concluding that genetic engineering is unlikely to play a significant role in increasing food production in the foreseeable future.

The report recommends that the U.S. Department of Agriculture, state agricultural agencies and universities increase research and development for proven approaches to boost crop yields. Those approaches should include modern conventional plant-breeding methods, sustainable and organic farming, and other sophisticated farming practices that do not require farmers to pay significant upfront costs. The report also recommends that U.S. food aid organizations make these more promising and affordable alternatives available to farmers in developing countries.

Last, the insect-resistant cotton Monsanto sold to Indian farmers turned out to be susceptible to disease, causing loss of harvest and thousands of suicides.

Edith Borie
Karlsruhe, Germany

Magic Pill

Regarding Gary Stix's cover story, "Turbocharging the Brain," at age 40 (nine years ago) I was a physical and mental wreck: I was way overweight, and my mathematical abilities seemed to be deteriorating. I found a magic pill that lowered my weight (by 20 percent) and my blood pressure and cholesterol (both now "normal"), revitalized my you-know-what drive, and made my mind stronger than ever. The pill I started taking: triathlon!

Alexander H. Slocum
Neil and Jane Pappalardo Professor
of Mechanical Engineering
Massachusetts Institute of Technology

Nonanarchist Pirates

Michael Shermer's Skeptic column, "Captain Hook meets Adam Smith," makes the common mistake about "anarchy" that it signifies disorder in social relations and the rule of the strongest by violence. Anarchy does not mean "social disorder." It means "no chief or ruler." Our common ignorance of the true meaning of anarchy persuades us that we need a violent Hobbesian state to "keep us all in awe." We might have a better aspiration for our future evolution.

Hugo du Coudray
Professor Emeritus
Portland State University

CLARIFICATIONS In "The Way the Wind Blows" [News Scan], Michael Moyer writes that "turbines are exponentially sensitive to changes in wind speed." That was not meant literally. Turbine power is proportional to the cube of wind speed.

In "The Crisis of Public Management" [Sustainable Developments], Jeffrey D. Sachs complains that the U.S. government has failed to build a single coal-fired plant that captures and sequesters its carbon dioxide. One such facility does exist at the Shady Point coal power plant in Oklahoma, but it is not a government project.

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Cosmic Dust ▪ Working Bacteria ▪ Yeast for Bread

Compiled by Daniel C. Schlenoff

FEBRUARY 1960

METEOR DUST—"The recent extension of geophysical investigations into nearby space has given emphasis to the fact that life on earth is shielded by the earth's atmosphere. Death from 'meteoritic stroke' might be a not-uncommon coroner's verdict if the protective canopy of the atmosphere were not spread above our heads. During the past 13 years I have been engaged in efforts to secure direct measurement of the meteoritic fallout. My samples of meteoritic dust and cosmic spherules have come from the tops of high mountains remote from industrial civilization, and from the bottom of the ocean. The data now show that meteoritic material comes down to earth in much larger quantity (about five million tons per year) than earlier estimates. Moreover, it appears that the rate of fall has varied during the past 10 or 15 million years. —Hans Pettersson"

FEBRUARY 1910

BACTERIA FERTILIZERS—"The discovery of the mechanism of nitrification and the fixation of atmospheric nitrogen by the bacteria of root nodules soon led to attempts to aid the process by the addition of nitrogen-fixing bacteria. In 1895 Nobbé and Hiltner patented a process of inoculating peas and beans and the soil in which they grow by soaking the seed with an infusion of a gelatin culture of the bacteria of the root nodules. In 1904 the United States Bureau of Agriculture distributed 12,000 boxes of bacterial cultures, which appear to have produced good results. But the effect of these preparations is uncertain. The soil naturally swarms with nitrifying bacteria, but their growth may be checked by various causes."

FLOODS—"The inundation of Paris made many of the streets of that metropolis as navigable as the canals of Venice [*see photograph*]. The highest point reached by the water was 31 feet 4 inches above the normal at the Pont Royal. Not since the historic flood of 1615 has Paris been visited by such an inundation. The banks have been overflowed for up to a mile on either side. The actual cause of the flood has not been fully revealed. Some explain it geologically by arguing that the basin of the Seine had become saturated during a mild winter, characterized by heavy rains and little evaporation. It will be safer to await the investigation of the municipal engineers."

CITY OF LIGHT becomes a city of water: Paris floods, 1910

SCIENTIFIC AMERICAN, VOL. CII, NO. 8, FEBRUARY 19, 1910

AGE OF STEAM—"The rapid elimination of the sailing vessel is shown by statistics recently given by a German paper. In the twenty years between 1888 and 1908, the percentage of sailing vessels has declined in the merchant marine of Great Britain from 44.1 to 12.6; of Germany, from 62.1 to 19.1; of the United States, from 80.7 to 30.9. In the merchant marine of France, however, but little change has occurred, the respective percentages being 47.9 to 47.2."

FEBRUARY 1860

BEST THING SINCE . . .—"Within the past 10 years there has been a revolution in making bread. The ancient leaven bread was made by the dough being left in a warm place till it began to ferment. The chemical progress is the starch into sugar, then carbonic acid and alcohol, which forms between the particles of flour and swells them up. But great care was required in the operation lest it be decomposed, and therefore the modern process by yeast is much more preferable. Within the past 10 years, besides yeast in making bread, we have had 'baking powders' and 'self-raising flour,' and such, and 99 families in 100 use some of these."

A PRACTICAL MAN—"Out West, they are going beyond anything ever attempted in reckless construction of railways. A western man, who, in his time, had been a merchant, a surveyor, an engineer, a land agent, a railway president and a professional politician (on more sides than one, by way of variety), once remarked to me, concerning a mutual acquaintance who was an engineer, 'a good theoretical man, sir, but requires millions [of dollars] to carry out his plans; he might do well in England, with an unlimited supply of money, but he is not calculated for our western country; not practical, sir, not practical! We want men that can build railroads of *corn cobs*, if necessary!'"

Energy & Environment

Poisoned Shipments

Are strange, illicit sinkings making the Mediterranean toxic? BY MADHUSREE MUKERJEE

IN OCTOBER 2009 THE GOVERNMENT OF Italy announced that a wreck discovered off the southwestern tip of the country is the *Catania,* a passenger vessel sunk during World War I—and not the *Cunski,* a cargo ship loaded with radioactive waste, as alleged by district authorities from nearby Calabria. Few locals are reassured, says Michael Leonardi of the University of Calabria. He and others maintain that the putative *Cunski* is still out there and is just one of numerous ships full of poisonous garbage that a crime syndicate has scuttled in the Mediterranean Sea. Such a startling allegation, if true, would not only damage the tourism and fishing industries along this idyllic coast but also compromise the health of Mediterranean residents.

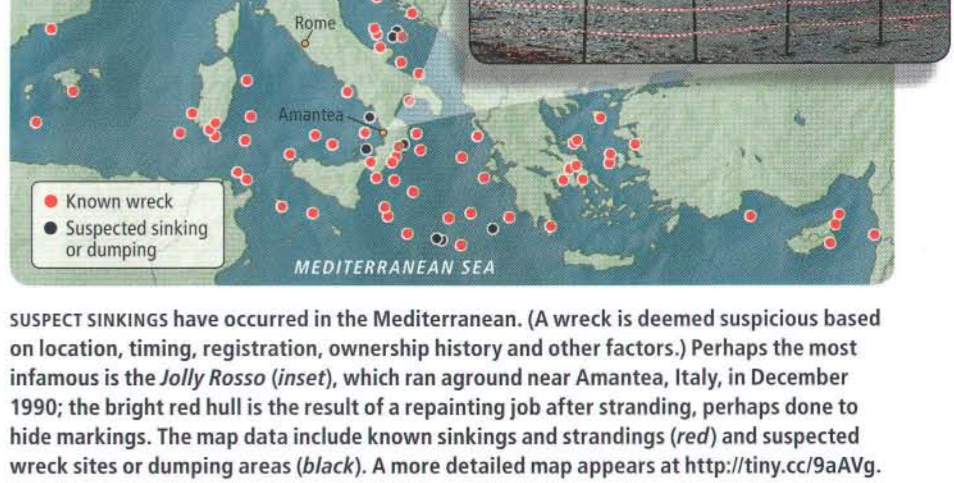
Processing and safely storing waste from the chemical, pharmaceutical and other industries can cost hundreds, even thousands, of dollars per ton—which makes illegal disposal highly profitable. According to the Italian environmental organization Legambiente, some waste shippers that have operational bases in southern Italy have been using the Mediterranean as a dump. While acknowledging that "no wreck has yet been found that contains toxic or radioactive waste," physicist Massimo Scalia of the University of Rome, La Sapienza, who has chaired two parliamentary commissions on illegal waste disposal, argues that other evidence makes their existence "beyond reasonable doubt."

Scalia contends that 39 ships were wrecked under questionable circumstances between 1979 and 1995 alone; in every case, he adds, the crew abandoned the ship long before it sank. An average of two ships per year suspiciously disappeared in the Mediterranean during the 1980s and early 1990s, according to Legambiente—and the number has increased to nine wrecks per year since 1995. Paolo Gerbaudo of the Italian daily *il Manifesto,* who is assisting investigations, has identified 74 suspect wrecks of which he regards 20 as being extremely suspicious. (The record extends until 2001.)

One notable example of a dubious wrecking is the *Jolly Rosso,* which washed up in December 1990 near the town of Amantea, after what investigators believe was a botched attempt to scuttle it. The cargo was offloaded and allegedly buried on land. In October 2009 an environmental ministry report noted that district authorities detected dangerous substances in a nearby river valley, including a buried concrete block containing mercury, cobalt, selenium and thallium at very high concentrations—and displaying substantial radioactivity indicative of synthetic radionuclides. Authorities also found marble granules mixed in with thousands of cubic meters of earth, which was contaminated with heavy metals and cesium 137, typically a waste product of nuclear reactors. The assemblage suggests that the *Jolly Rosso*'s cargo included radioactive waste, sealed in concrete and shielded from detection by marble dust (which absorbs radioactivity).

Significantly, the increase in the frequency of wrecking correlates with the progressive tightening of international dumping regulations. The first suspect sinking, in 1979, occurred the year after the Barcelona Convention, which restricts the disposal of pollutants in the Mediterranean Sea, came into force. Over the following decades other treaties expanded the regulations, culminating in a 1993 amendment to the London Dumping Convention that halted the ocean disposal of all radioactive waste and in a 1995 amendment to the Basel Convention that banned the deposition of the industrial world's lethal excreta in developing countries. The

Suspicious Cargo Shipwrecks, 1979–2001



SUSPECT SINKINGS have occurred in the Mediterranean. (A wreck is deemed suspicious based on location, timing, registration, ownership history and other factors.) Perhaps the most infamous is the *Jolly Rosso* (*inset*), which ran aground near Amantea, Italy, in December 1990; the bright red hull is the result of a repainting job after stranding, perhaps done to hide markings. The map data include known sinkings and strandings (*red*) and suspected wreck sites or dumping areas (*black*). A more detailed map appears at http://tiny.cc/9aAVg.

SCIENTIFIC AMERICAN, SOURCE: DATA COMPILED BY PAOLO GERBAUDO *il Manifesto* AND DAVID BOARDMAN *Massachusetts Institute of Technology* (map); COURTESY OF LEGAMBIENTE (boat)

laws ruined the ambitious plans of one firm, Oceanic Disposal Management, incorporated in the British Virgin Islands, to drop tens of thousands of cubic meters of radioactive waste into the seabed off the African coast. Andreas Bernstorff, who formerly headed a Greenpeace campaign against the trade in toxic waste, reports that the number of schemes to ship such garbage to Africa fell steeply at this time, to at most one attempt per year. The drop coincides with a sudden and ominous rise in the frequency with which ships in the Mediterranean perished.

Despite profound concern in southern Italy, efforts to find the wrecks and identify their cargo have been slow. The endeavor is expensive, Scalia notes, and requires "serious engagement by magistrates and politicians"—which, but for "a few honorable exceptions," has been lacking. Fear of violence may also have hindered investigation. In 1994 Italian television journalist Ilaria Alpi and cameraman Miran Hrovatin were shot dead near Mogadishu, after they picked up the hazardous waste trail in Somalia, where political upheaval has kept the country from enforcing controls.

That African nation possibly holds clues to the kinds of health hazards Italians might face. "My committee heard from Somalians who said many people in that area had symptoms of poisoning and some died," Scalia attests, referring to a stretch of highway along which Alpi and Hrovatin may have witnessed the offloading of toxic substances. The tsunami of December 2004 dredged up giant metal containers from the seabed and placed them on Somali beaches—proving that the country's coastal waters had also received questionable trash. A United Nations report blamed fumes from these unidentified objects for internal hemorrhages and deaths of local people.

In April 2007 Calabrian authorities had temporarily halted fishing in waters off Cetraro (where the *Cunski* lies, according to a turncoat from the 'Ndrangheta mafia) because of dangerous levels of heavy metals in marine sediment. In the region around Amantea, mortality from cancer between 1992 and 2001 exceeded that in neighboring areas, a study found; just as worrisome, hospitalizations for certain malignancies have risen in recent years.

"Almost all the coastal regions of our country may be compromised," warned 28 Italian legislators from opposition parties on October 1, in a parliamentary motion demanding that the sunken ships be located and their contents secured. Until investigators can salvage the truth about the shipwrecks, suspicion and anxiety will plague the Mediterranean shores.

Madhusree Mukerjee is author of the forthcoming book Churchill's Secret War, *about England's famine-inducing colonial policies during World War II (Basic Books 2010).*

Negating "Climategate"

Copenhagen talks and climate science survive stolen e-mail debacle **BY DAVID BIELLO**

REUTERS

CLIMATE CLAMOR: Demonstrators in Copenhagen at December rally in a call for action.

COPENHAGEN—EVEN UNDER THIS CITY'S LOW, LEADEN SKIES, at least one thing remained clear as leaders from 193 countries gathered to negotiate climate agreements: one ton of carbon dioxide emitted in the U.S. has the same effect as one ton emitted in India or anywhere else. That simple truism is part of a huge body of data pointing to humanity's effect on climate, and for most negotiators, the weight of that evidence seems to have crushed any doubt they may have felt in the wake of the 1,000-plus e-mails and computer code stolen from the University of East Anglia's Climatic Research Unit (CRU).

The theft made headlines as "Climategate" in November, and many private correspondences among scientists became public. Climate contrarians and politicians, including Senator James M. Inhofe of Oklahoma, have claimed that the messages show that climate science was far from settled, that "tricks" were used and that researchers hid unfavorable data.

In fact, nothing in the stolen material undermines the scientific consensus that climate change is happening and that humans are to blame. "Heat-trapping properties can be verified by any undergraduate in any lab," notes climate scientist Katharine Hayhoe of Texas Tech University. "The detection of climate change, and its attribution to human causes, rests on numerous lines of evidence." They include melting ice sheets, retreating glaciers, rising sea levels and earlier onset of spring, not to mention higher average global temperatures.

"Further increases in greenhouse gases will lead to increasingly greater disruption," said meteorologist Michael E. Mann of the Pennsylvania State University in a December 4 conference call with reporters. Mann was among the scientists whose e-mails were exposed.

Some of the kerfuffle rests on a misreading of the e-mails' wording. For example, "trick" in one message actually describes a de-

cision to use observed temperatures rather than stand-in data inferred from tree rings. Instead of implying deception, the word itself in science often refers to a strategy to solve a problem. Even those scientific papers specifically challenged by the e-mails—one message vowed to keep them out of a report by the United Nations's Intergovernmental Panel on Climate Change "even if we have to redefine what the peer-review literature is"—nonetheless made it into the most recent IPCC report.

Even if the CRU data "were dismissed as tainted, it would not matter," argues IPCC contributor Gary Yohe of Wesleyan University. "CRU is but one source of analysis whose conclusions have been validated by other researchers around the world." Other sources include NASA's Goddard Institute for Space Studies, the National Oceanic and Atmospheric Administration's National Climatic Data Center, and even the IPCC, all of which provide access to raw data.

But the messages revealed at least one lapse in judgment when CRU director Phil Jones sent Mann an e-mail asking him to delete any correspondence related to "AR4," referring to an upcoming IPCC report. "To my knowledge, no one acted on that request. I did not delete any e-mails," Mann said. The continuing existence of the e-mail itself would seem to support his contention, although his response at the time was to agree to contact a fellow scientist, "Gene," as requested by Jones, who has stepped down as CRU director.

The stolen e-mails may ultimately provide a sociological window into the climate science community. "This is a record of how science is actually done," notes Goddard's Gavin A. Schmidt. Historians will see "that scientists are human and how science progresses despite human failings. They'll see why science as an enterprise works despite the fact that scientists aren't perfect."

"Science has already played its role" in the climate debate, explains Rajendra Pachauri, chair of the IPCC. After all, IPCC authors had to achieve consensus with more than 190 countries as well as publicly respond to each comment on the draft documents. "Unfortunately, the [climate] negotiations are becoming solely political," Pachauri laments. So the theft could become a factor. "Do I think it will have a significant effect on the judgment of lawmakers or public opinion? No, I don't," remarks atmospheric scientist Michael Oppenheimer of Princeton University. "But you never know with these things."

Python Boom

Big snakes poised to change U.S. ecosystems BY MICHAEL TENNESEN

BROUGHT TO THE U.S. AS PETS, BURMESE pythons have made headlines with their uncontrolled spread in the Florida Everglades and willingness to challenge alligators for the position of top predator. A report released by the U.S. Geological Survey last fall delivered more bad news: two other constrictor species, also former pets, are thriving in the area, and six others could pose similar threats. Researchers fear that reproductive populations could spread and eat native animals into extinction.

RETICULATED PYTHONS and other constrictors are spreading in the U.S. more quickly than expected and threaten local wildlife.

The new interlopers—northern and southern African pythons, reticulated pythons, boa constrictors and four species of anacondas—have "ecological similarities," explains Robert Reed, a USGS biologist and one of the authors of the report. "They are large invasive predators that native birds and mammals aren't adapted to, and they are highly fecund, capable of producing up to 100 hatchlings in one nest." They're also big; some grow up to 20 feet and 200 pounds. They seize prey with their teeth and then wrap around the prey's body, squeezing it to death.

Biologists first noticed the slithering invasion in the late 1990s. Snake numbers have risen dramatically: in 2000 two Burmese pythons were captured in the Everglades National Park; in 2008 the number captured hit 343. Biologists believe that tens of thousands now live in the park. Other constrictors have begun appearing beyond the Everglades: boa constrictors south of Miami and African pythons just west of the city.

Cryptic by nature, constrictors are extremely difficult to capture. "We know how they move and what they look like," says USGS biologist Kristen Hart. "We had a radio-tagged snake in a fenced-off area the other day, right in the middle of six of us, and yet we couldn't even see it. They are often underground or underwater or in a tree. They blend in so well here in the Everglades."

When they move, however, they can move far. Relocated pythons have demonstrated a homing ability, returning up to 48 miles to the place where they were captured. Biologists worry that the reptiles may populate the Florida Keys, perhaps by riding on floating logs or even swimming the distance.

Without native predators, the snakes could really thrive. In fact, Burmese pythons may do better in Florida than in their home ranges in Southeast Asia, where jackals, monitor lizards, disease and parasites limit their numbers. "By the time they reach two years of age, not much can eat them in the Everglades," Hart states. She describes one python she captured that "threw up four feet of an alligator." Although biologists have recovered 10 alligators in python stomachs, for the most part the constrictors prey on small mammals and birds.

This predilection concerns Dave Hallac, chief of biological resources for the Everglades and Dry Tortugas. "We are going

BJORN LARDNER *Colorado State University*; COURTESY OF USGS

through this comprehensive restoration program here in the Everglades, trying to restore a number of wading and water-dependent birds, yet at the same time we have this big new predator in our midst." Hallac and others do not want a repeat of what happened on the American island of Guam. There the nonnative brown tree snake invaded shortly after World War II and devastated native wildlife. Since the snake's arrival, most likely as stowaways on cargo vessels, Guam has lost 10 of its 12 native forest bird species, most of its bats and about half of its lizards.

Given the number of constrictors imported to the U.S. as pets—Reed pegs the figure at just under one million—some species appear poised to take up permanent residence. (Florida law stipulates jail terms up to one year for anyone releasing a pet constrictor, which can grow from a 20- inch-long juvenile to an eight-foot-long monster in a year.) Still, wildlife biologists hope to keep the invasion contained. Although much of the southern U.S. offers a hospitable climate, the availability of prey, habitat and other factors will affect the snakes' success.

Hart and others are working with different traps, transmitters and "Judas snakes"—radio-tagged pythons that lead them to other snakes—in an attempt to understand and control the creatures. She laments the fact that Florida didn't take a more aggressive stance against these snakes years ago, when the reptiles were first sighted and might have been eradicated quickly. Says Hart: "We've gone beyond the point where they're easily controllable."

Michael Tennesen is a freelance science writer based near Los Angeles.

Medicine & Health

Mouse Mash-Up

To better study disease, mice that reflect human DNA diversity BY MEGAN SCUDELLARI

RESEARCH TRIANGLE PARK, N.C.—THE MICE ARE PRETTY ODD. Distributed among 2,000 cages, they represent a real hodgepodge: white, black and brown mice, some fat, some skinny, some with crooked tails, some huddling in corners while others scamper in circles. These mice from the University of North Carolina at Chapel Hill, awaiting a new housing facility here, aren't mutant rejects. Instead they are a valuable new resource—the most diverse mouse strains to ever hit the lab bench. Because they more closely reflect the genetic variation of humans, they may be the key to understanding some of today's most common, and most complex, diseases.

The mice don't have the rodent equivalent of human ethnicity; rather they simply have much greater DNA diversity. Traditional laboratory mice have a limited number of alleles—that is, different versions of the same gene. Their DNA contains only about 30 percent of the allelic diversity of the entire mouse genome, meaning that lab mice as a whole have only a few forms of each gene compared with their wild counterparts. But now geneticists have begun breeding a massive new mouse population, one that encompasses 90 percent of the diversity of the mouse genome and is on par with the natural variation in the human genome.

The idea of creating these mouse strains took shape at a conference in 2001, when a handful of scientists began to commiserate over the lack of progress in the study of illnesses caused by many genes acting together. In such complex diseases, which include cancer and diabetes, scientists glean just bits of information from traditional mouse genetics, which typically involves silencing one gene at a time. "We needed a new population of animals to stimulate the field," says David W. Threadgill, a geneticist at North Carolina State University and a leader of the project. So the researchers outlined a plan: Start with genetically diverse founding strains and breed them into hundreds of reproducible varieties with a wide range of physical and behavioral characteristics. They would have combinations of traits that today's lab mice just don't possess. The scientists calculated that only eight founding strains were enough to capture the desired allelic diversity while keeping the project practically and computationally manageable.

COURTESY OF BRYNN H. VOY *University of Tennessee*

VARIETIES GALORE: Mice bred from the Collaborative Cross show many traits. The project aims to mimic the genomic diversity seen in humans, to better model complex diseases.

But the project, called the Collaborative Cross (CC), was more easily imagined than executed. A previous attempt to create genetically diverse mouse lines by chemically inducing mutations lost funding because of low demand, so geneticists weren't willing to funnel a cool $50 million, the initial CC price tag, into another mouse project. "If the National Institutes of Health pours a lot of money into it, and it doesn't have a lot of impact, credibility is hurt," says Alan D. Attie, a geneticist at the University of Wisconsin–Madison who is not involved in the project.

But confident and impatient, Gary Churchill, a geneticist at the Jackson

Laboratory in Bar Harbor, Maine, began breeding the initial eight strains in his own lab, including three wild-derived strains that contribute 75 percent of the genetic diversity of the CC. Soon the collaborators pieced together enough funding to commence breeding in earnest, first at Oak Ridge National Laboratory in Tennessee, later at U.N.C., Tel Aviv University in Israel, and the University of Western Australia in Perth. Today the first few strains are almost finished breeding, and the team hopes to have the initial 50 lines done by the end of 2010 and 300 to 500 completed by 2013—and at a cost of about one-tenth the original estimate.

"But we can't be sitting around on our hands," Churchill says, so he and others have already begun using the lines, called the pre-CC, to demonstrate the usefulness of the mice, in studies ranging from basic physiology to the animals' susceptibility to infectious diseases. The initial forays are drawing interest from federal agencies: last September the U.S. awarded U.N.C. $8.6 million for a center to study the genetics of human psychiatric disorders using the CC.

Scientists outside the project are being lured, too. Samir Kelada, a postdoctoral fellow in the lab of NIH head Francis Collins, has already used around 160 pre-CC mice to study gene-environment interactions that cause allergic asthma. They include those that remain perfectly healthy after receiving large doses of asthma allergens and those that wheeze before testing even begins. "They're just so diverse," Kelada says.

The CC leaders hope that more researchers like Kelada will use the freely available resource. Unless the project's founders, who are primarily geneticists, can convince physiologists and biochemists to examine the mice, "the impact is going to be very limited," Attie says. Threadgill agrees: "There is no doubt we have to bring in people who are experts in physiology and behavior. We really want it to be a community resource."

Megan Scudellari is a freelance science writer based in Durham, N.C.

Testosterone-Fueled Sociability

Do those with more testosterone coursing through their bodies make riskier, more aggressive decisions? To test the popular idea, researchers from Switzerland and the U.K. gave 121 women either 0.5 milligram of the hormone or a placebo and had them play an ultimatum bargaining game in pairs. With real money on the line, one player of the pair had to propose how to split the funds. The other player could reject the offer if she thought it unfair—and if the game ended in a stalemate, no money was distributed.

Given the common wisdom about testosterone, the players who had gotten the testosterone boost should be more likely to take a riskier, more antisocial approach and make a lowball offer in an effort to keep more of the pot. The behavior of the test subjects, however, did not confirm the stereotypes, according to results published online December 8 by *Nature* (*Scientific American* is part of Nature Publishing Group). Those who had received testosterone actually made higher offers than those who had gotten the placebo.

Evidently, the testosterone-fueled proposals reduced bargaining conflicts and facilitated the exchange. Those with more of the hormone may have been acting out of a desire to maintain their images by avoiding rejection. The results do not necessarily mean that testosterone has no role in complicating social negotiations, but such a contribution is likely to be more complex than previously thought. —*Katherine Harmon*

Research & Discovery

Lost Giants

Did mammoths vanish before, during *and* after humans arrived? BY CHARLES Q. CHOI

BEFORE HUMANS ARRIVED, THE AMERI-CAS WERE HOME TO woolly mammoths, saber-toothed cats, giant ground sloths and other behemoths, an array of megafauna more impressive than even Africa boasts today. Researchers have advanced several theories to explain what did them in and when the event occurred. A series of discoveries announced last fall, at first glance apparently contradictory, add fresh details to the mystery of this mass extinction.

One prominent theory pegs humans as the cause of the demise, often pointing to the Clovis people, who left the earliest clear signs of humans entering the New World roughly 13,500 years ago. The timing coincides with the disappearance of megafauna, suggesting the Clovis hunted the animals to extinction or infected them with deadly disease. Another hypothesis supposes that climate was the culprit: it had swung from cold to warm twice, including a 1,300-year-long chill known as the Younger Dryas; such abrupt shifts might have overwhelmed the creatures' abilities to adapt.

To pin down when the megafauna vanished, paleoecologist Jacquelyn Gill of the University of Wisconsin–Madison and her colleagues analyzed fossil dung, pollen and charcoal from ancient lake sediments in Indiana. The dung of large herbivores harbors a fungus known as *Sporomiella*, and its amounts in the dung gives an estimate of how many mammoths and other megafauna were alive at different points in history. Pollen indicates vegetation levels, and charcoal signals how many fires burned; the extent of flora and wildfires is related to the presence of herbivores, the researchers say in the November 20 *Science*. Without megaherbivores to keep them in check, broad-leaved tree species such as black ash, elm and ironwood claimed the landscape; soon after, buildups of woody debris sparked a dramatic increase in wildfires. Putting these data together, Gill and her team conclude that

MYSTERY DEATHS: **Mastodons, depicted here munching on black ash trees, and other megafauna vanished long ago. Some seemed to have survived humanity's arrival in the Americas.**

the giant animals disappeared 14,800 to 13,700 years ago—up to 1,300 years before Clovis.

A different study, however, suggests that this mass extinction happened during Clovis. Zooarchaeologist J. Tyler Faith of George Washington University and archaeologist Todd Surovell of the University of Wyoming carbon-dated prehistoric North American mammal bones from 31 different genera (groups of species). They found that all of them seemed to meet their end simultaneously between 13,800 to 11,400 years ago, findings they detailed online November 23 in the *Proceedings of the National Academy of Science USA*.

But if ancient DNA recovered from permafrost is any sign, megafauna survived in the New World millennia after humanity arrived. As the permafrost in central Alaska cracked during springtime thaws, water that held DNA from life in the region leaked in, only to freeze again during the winter. As such, these genes can serve as markers of "ghost ranges"—remnant populations not preserved as fossil bones. Looking at mitochondrial DNA, evolutionary biologist Eske Willerslev of the University of Copenhagen and his colleagues suggest mammoths lasted until at least 10,500 years ago (as did horses, which actually originated in the Americas only to vanish there until the Europeans reintroduced them). The *Proceedings of the National Academy of Science USA* published those findings online December 14.

Although the three papers appear to conflict with one another, they could be snapshots from the beginning, middle and end of a mass extinction. "If they seem to disagree, it is for the same reason as in that fable about the three blind men trying to describe an elephant—or mammoth?—by touching different parts of it," says ecologist Christopher Johnson of James Cook University in Australia, who did not take part in any of the studies.

Johnson suggests the fungus research is superb evidence for when the decline began, but it is not as good at confirming exactly when the extinction was completed, especially over larger areas where sparse populations might have persisted. The DNA finds, on the other hand, can detect late survivors, he says, "maybe very close to the actual time that the last individuals were alive, at least in Alaska." The bones analyzed from the period roughly in between show that the extinction process afflicted many species simultaneously. Those fossils came from the contiguous U.S., which back then was separated from Alaska by the massive Laurentide and Cordilleran ice sheets and so, Faith notes, could explain why the pattern of extinction differed up there.

So what caused the decline? The jury's still out, says Willerslev's collaborator Ross MacPhee of the American Museum of Natural History in New York City. Johnson notes that archaeologists are turning up evidence of humans in the New World before Clovis, and he suggests they overhunted the megafauna. The beautifully crafted fluted spear points linked with the Clovis might reflect strategies that developed once the giants became rare and harder to hunt, Johnson adds.

Even if scientists cannot definitively finger the killer, research into the megafauna disappearance "is directly relevant today because we are in the middle of a mass extinction and one for which we know the cause—us," Gill says. "Large animals are among the most threatened today," she points out, and no one wants Africa to follow the ancient experience of the Americas.

Charles Q. Choi is a frequent contributor based in New York City.

Hearing with Skin

Saying words such as punt, tackle and kick produces a puff of air that helps the listener distinguish words with similar letter sounds, even though the puffs are so subtle that they go unnoticed. Bryan Gick and Donald Derrick of the University of British Columbia set out to determine if these puffs enhance auditory perception. They had 66 participants listen to recorded sounds while receiving light, imperceptible bursts of air from thin tubes placed either over their hand or neck or in their ear.

In some cases, puffs came with the appropriate sounds ("pa" and "ta"), at other times not ("ba" and "da"). Without any puffs, participants misheard "pa" for "ba" and "ta" for "da" 30 to 40 percent of the time. The accuracy improved 10 to 20 percent when heard with an accompanying air puff over the hand or neck. No improvement took place, however, when an air puff went into the ear, suggesting that the participants were not simply hearing the airflow.

The opposite effect occurred when the volunteers received a puff with the inappropriate sounds "ba" and "da": the accuracy decreased by about 10 percent if the sounds came with puffs. The researchers described their work, which might lead to improved hearing aids, in the November 26 *Nature* (*Scientific American* is part of Nature Publishing Group).

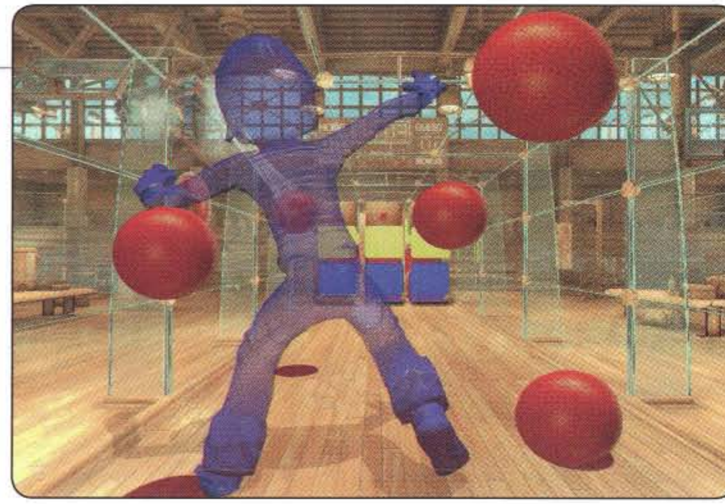
—*Carina Storrs*

COURTESY OF BARRY ROAL CARLSEN/UNIVERSITY OF WISCONSIN–MADISON

Technology

Naked Gaming

Good-bye, controller: an Xbox upgrade reads natural gestures BY SUSAN KUCHINSKAS



GAME ON: **Microsoft's answer to the Wii, called Natal, responds to gestures of players, who in this game must block a barrage of balls.**

WHEN NINTENDO'S WII GAME CONSOLE DEBUTED IN November 2006, its motion-sensing handheld "Wiimotes" got players off the couch and onto their feet. Now Microsoft hopes to outdo its competitor by eliminating the controller altogether: this past January it revealed details of Project Natal, which will give Xbox 360 users the ability to manipulate on-screen characters via natural body movement. The machine-learning technology will enable players to kick a digital soccer ball or swat a handball simply by mimicking the motion in their living room.

Microsoft, which announced its ambitious Xbox upgrade plan in June 2009, has not set a release date, but many observers expect to see Natal at the end of the year. It will consist of a depth sensor that uses infrared signals to create a digital 3-D model of a player's body as it moves, a video camera that can pick up fine details such as facial expressions, and a microphone that can identify and locate individual voices.

Programming a game system to discern the almost limitless combinations of joint positions in the human body is a fearsome computational problem. "Every single motion of the body is an input, so you'd need to program near-infinite reactions to actions," explains Alex Kipman, Microsoft's director of innovation for Xbox 360.

Instead of trying to preprogram actions, Microsoft decided to teach its gaming technology to recognize gestures in real time, just like a human does: by extrapolating from experience. Jamie Shotton of Microsoft Research Cambridge in the U.K. devised a machine-learning algorithm for that purpose. It also recognizes poses and renders them in the game space on-screen at 30 frames per second, a rate more than sufficient to convey smooth motion. Essentially, a Natal-enhanced Xbox will capture movement on the fly, without the need for the mirror-studded spandex suit of conventional motion-capture approaches.

Training Natal for the task has required Microsoft to amass a large amount of biometric data. The firm sent observers to homes around the globe, where they videotaped basic motions such as turning a steering wheel or catching a ball, Kipman says. Microsoft researchers later laboriously selected key frames within this footage and marked each joint on each person's body. Kipman and his team also went into a Hollywood motion-capture studio to gather data on more acrobatic movements.

"During training, we need to provide the algorithm with two things: realistic-looking images that are synthesized and, for each pixel, the corresponding part of the body," Shotton says. The algorithm processes the data and changes the values of different elements to achieve the best performance.

To keep the amount of data manageable, the team had to figure out which were most relevant for training. For example, the system doesn't need to recognize the entire mass of a person's body, but only the spacing of his or her skeletal joints. After whittling down the data to the essential motions, the researchers mapped each unique pose to 12 models representing different ages, genders and body types.

The end result was a huge database consisting of frames of video with people's joints marked. Twenty percent of the data was used to train the system's brain to recognize movements. Engineers are keeping the rest in a "ground truth" database used to test Natal's accuracy. The better the system can recognize gestures, the more fun it will be to play the game.

Of course, Microsoft is not the only company exploring gestural interfaces. Last May, Sony demonstrated a prototype unit that relies on stereo video cameras and depth sensors that, it says, could be used to control a computer cursor, game avatar or even a robot. Canesta, a company that makes computer-vision hardware, has demonstrated a system that lets couch potatoes control the TV with a wave of the hand and has partnered with computer manufacturers Hitachi and GestureTek to create gestural controls for PC applications.

Still, the controller should not disappear altogether, says Hiroshi Ishii, who is head of the Tangible Media Group at the M.I.T. Media Laboratory. "I'm a strong believer in having something tangible in your hand," he says. Wiimote devices, moreover, provide haptic feedback, such as vibration or resistance, which makes the action more realistic. Even for activities like Natal's soccerlike Ricochet game demo, Ishii points out, a player might miss the feeling of connecting with a physical object that a controller provides.

But Peter Molyneux, creative director of Microsoft Game Studios Europe, looks forward to a new breed of computer entertainment, because eliminating game controllers opens up more creative possibilities. "Natal is forcing me as a designer to think of this as a relationship between the player and a piece of technology," he says. "We're trying to make something that feels as if it's alive."

Susan Kuchinskas covers technology from Berkeley, Calif.

Bigger, Better Broadband

New regulatory rules should change the way Americans get online BY MICHAEL MOYER

AT THE TURN OF THE MILLENNIUM, THE U.S. HAD SOME OF THE best broadband access in the world. It reached more homes, and at a lower price, than most every other industrial country. Ten years later the U.S. is a solid C-minus student, ranking slightly below average on nearly every metric.

Just how the U.S. lost its edge and how it plans to get it back are the issues before the Federal Communications Commission as it prepares to launch the most significant overhaul of network policy since the birth of the Web. As part of last year's stimulus package, Congress provided $7.2 billion to expand broadband access to every American. It also required the FCC to outline a plan for how to make that happen. The outcome of the FCC's deliberations, due February 17, could determine not just control over the broadband infrastructure but also the nature of the Internet itself.

Today about 51 percent of U.S. households have broadband access, and those that do pay roughly $45 per month. Contrast that with South Korea, where 94 percent of households browse the Web at $37 per month (and at download speeds on average eight times quicker). According to an October report to the FCC from the Berkman Center for Internet & Society at Harvard University, the decline in the adoption, pricing and speed of broadband in the U.S. can be traced back to a series of key decisions made by the FCC nearly a decade ago.

These decisions limited most Americans to one or two choices of Internet service provider (ISP)—either the cable company or the telephone company. This is not the case in the rest of the industrial world. There so-called open-access policies mandate that the company that owns the physical infrastructure must sell access to those lines on a wholesale market. For example, France Telecom owns the telephone lines, yet consumers can choose from a number of different Internet service providers, each of which leases access from France Telecom's infrastructure.

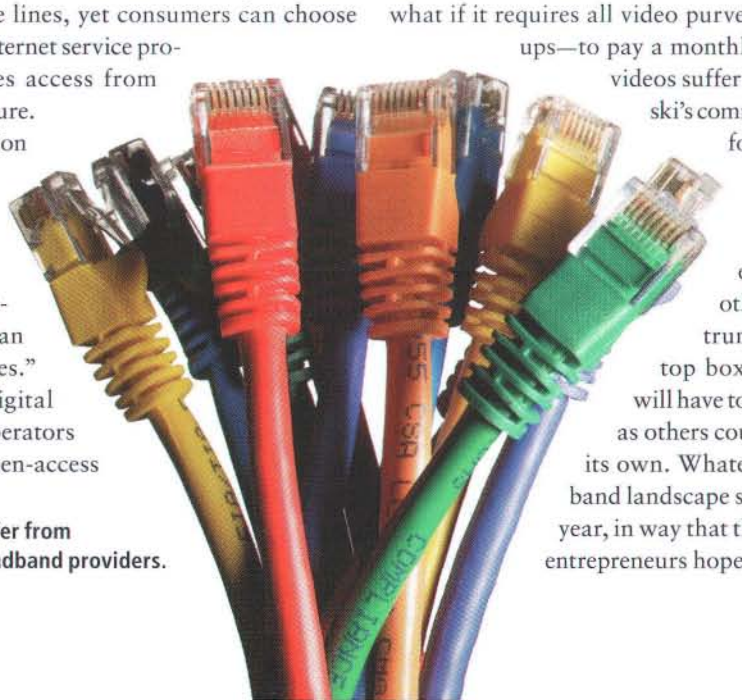
In the U.S., that competition doesn't exist. The reason is that in early 2002, then FCC commissioner Michael Powell reclassified broadband Internet services as "information services" rather than "telecommunications services." The ruling allowed DSL (digital subscriber line) and cable operators to avoid falling under the open-access rules mandated by the 1996 Telecommunications Act. At the time, Powell justified the decision by saying that it was the best way to fast-track greater broadband deployment.

The evidence to date has not supported this strategy. "When we look at the countries that have the highest speeds and the lowest prices," says Yochai Benkler, a professor at Harvard Law School and lead author of the Berkman report, "there is a clutch of competitors who entered over the past seven or eight years using open access to build their own competing advantages—agile, innovative competitors that catalyze the market." By reclassifying broadband services yet again, the FCC could bring those advantages to the U.S.

The upcoming FCC report is also expected to address the controversial matter of "Net neutrality." "Why has the Internet proved to be such a powerful engine for creativity, innovation and economic growth?" asked Julius Genachowski, chair of the FCC, in a recent speech. "A big part of the answer traces back to one key decision by the Internet's original architects: to make the Internet an open system." The structure of the Internet allows any user to access any site—and any entrepreneur to reach any user. It's now a cliché, but Web giants like Facebook and Google were started by students in bedrooms. They never could have flourished without access to an open-distribution system.

That openness has recently come under threat from some Internet service providers. Citing the strain on their infrastructure from peer-to-peer file sharing, ISPs have expressed an interest in blocking or degrading some content as it passes through their lines. Yet this ability would open a Pandora's box. What if Comcast, the anticipated new owner of the media company NBC Universal, decides to throttle back video from its competitor CBS? Or what if it requires all video purveyors—even shoestring startups—to pay a monthly transmission fee, lest their videos suffer delays in transit? Genachowski's comments suggest that the FCC will formalize the information agnosticism that has been built into the Web from its birth.

The final report is expected to touch on a huge swath of other issues, from wireless spectrum allocation to television set-top boxes. Some recommendations will have to go through Congress, whereas others could be enforced by the FCC on its own. Whatever the outcome, the broadband landscape should look very different in a year, in way that the next generation of Internet entrepreneurs hope will be level and fair.



PLUG 'N PAY: U.S. consumers suffer from a dearth of choices among broadband providers.

GETTY IMAGES

Comparatively Easy

Weighing the risks and benefits of medical procedures is unquestionably a good thing

BY THE EDITORS

Amid all the political battlefronts in the effort to reform our multi-trillion-dollar health care system, some of the most potentially worthwhile initiatives have received little notice—and the notice they *have* received has threatened to undo them. Each of the health care bills under consideration as we went to press creates a government-supported institute to oversee research comparing the effectiveness of existing medical treatments and practices. The American Recovery and Reinvestment Act of 2009 also allotted $1.1 billion to comparative effectiveness research (CER), whose results are expected to begin appearing within a year or so.

To guide the spending of that money, the National Institute of Medicine made a priority list of situations for which data about outcomes are badly needed—for instance, comparing the effectiveness of various medical and behavioral interventions to prevent the elderly from falling (the complications of which are a leading cause of death), comparing assorted drugs and surgeries alone or in combination in the treatment of specific cancers, comparing the effectiveness of different implants and devices for treating hearing loss, and so forth. In most cases, the recommendations explicitly state the goal is to compare the effectiveness of treatments and practices in specific patient populations. In other words, not to seek one-size-fits-all answers.

Yet many people have gotten the wrong impression that CER is little more than an excuse to ration care. In early December, Senator Lisa Murkowski of Alaska attempted to insert an amendment to the health care bill forbidding insurers from denying coverage of medical tests or treatments based on comparative effectiveness research findings. She was responding to the brief but loud controversy over a study last fall that questioned the value of routine yearly mammograms for women younger than 50. A study panel appointed by the U.S. Preventive Services Task Force reviewed available evidence and concluded that a blanket recommendation for women to have annual mammograms starting at age 40 is unwarranted. By the group's calculation, the mass screenings incurred a high likelihood of invasive follow-up testing and anxiety while finding a relatively small number of cancers that would have been lethal if they were caught later. To save 10,000 lives through early detection of tumors, one analysis found, 19 million women in their 40s would have to be screened over 10 years.

Advocates of cutting health spending did not help matters by noting that those figures could add up to $20 million per life saved. The cost-benefit discussion left the impression that the panel had judged the value of those 10,000 hypothetical women's lives and decided that the price of saving them was too high. But the report could and should have been interpreted differently. It assessed risks, not costs, versus benefits. And it did not say that mass screening is ineffective at catching deadly cancers, merely grossly inefficient, which is as much a commentary on the inadequacies of current screening technologies as on the ineffectiveness of blanket prescriptions.

To make informed decisions, any individual and his or her doctor need evidence, so comparative effectiveness research should, in principle, make more personalized medicine possible. The goal of CER is not to identify the most effective test or therapy for the great majority and impose it on everyone. Nor is it to ration health care—if CER finds that the more expensive treatment is also the most effective, so be it.

Senator Murkowski's amendment was ultimately defeated, but Senator Barbara Mikulski of Maryland succeeded in adding language to the bill requiring insurers to cover mammograms that doctors deem prudent, and Senator David Vitter of Louisiana added, by unanimous consent, a directive telling the government to disregard the latest task force recommendations. This fear and misunderstanding of comparative effectiveness research are unfortunate. Used properly, the CER studies should give us better medicine, not take it away. That should make support and protection for comparative effectiveness research one of the easiest pieces of the health care puzzle to resolve. ■

ILLUSTRATION BY MATT COLLINS

Fixing the Broken Policy Process

Greater transparency and limits on lobbyist influence would promote better long-range strategies

BY JEFFREY D. SACHS

The breakdown of the Washington policy process has four manifestations. First is a chronic inability to focus beyond the next election. "Shovel-ready" projects squeeze out attention to vital longer-term strategies that may require a decade or more. Second, most key decisions are made in congressional backrooms through negotiations with lobbyists, who simultaneously fund the congressional campaigns. Third, technical expertise is largely ignored or bypassed, while expert communities such as climate scientists are falsely and recklessly derided by the *Wall Street Journal* as a conspiratorial interest group chasing federal grants. Fourth, there is little way for the public to track and comment on complex policy proposals working their way through Congress or federal agencies.

These failings take a special toll on the challenges of sustainable development because there is no quick fix, for example, for the challenge of large-scale reductions in greenhouse gas emissions. Instead of getting long-term strategies for adopting low-carbon energy sources, upgrading the power grid, encouraging electric transportation and so on, we are getting cash for clunkers, subsidies for corn-based ethanol, and other ineffective and highly costly nonsolutions delivered by large-scale lobbying.

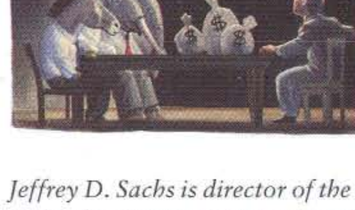
Some free-market economists say sustainable development should be left to the marketplace, but the marketplace now offers no incentive to reduce carbon emissions. Even putting a levy on carbon emissions, either through a carbon tax or carbon-emission permits, will not be sufficient. The development and deployment of major technologies potentially crucial to more sustainable energy—such as nuclear power, wind and solar power, biomass conversion and transport infrastructure—are matters of systems design requiring a mix of public and private decision making.

Herein lies the policy challenge today. When we let the private sector enter into public decision making, we end up with relentless lobbying, money-driven politics, suppression of new technologies by incumbent interests and sometimes miserable choices devoid of serious scientific content. How can business and government work together without policies falling prey to special interests?

First, the administration should initiate a more open, transparent and systematic public-private policy process in each major area of sustainable development. Highest priorities would include renewable energy, nuclear power and carbon capture and sequestration. A high-level roundtable would be established in each area, perhaps under the National Academy of Sciences, with representatives of private business, nongovernmental organizations, government officials, scientists and engineers. The proceedings would be open to the public, Web-based, and available for submissions and testimony by interested parties. Each roundtable would prepare a report within six to 12 months containing a technical overview and policy options, prepared for both the president and Congress. Second, the administration would prepare draft legislation, on which the experts on the roundtables and the general public would be invited to comment through Web-based submissions. Third, the congressional processes, too, would become Web-supported. Hearings and testimony would be open to the public, and Web sites would encourage comments and additional evidence.

These measures would infuse the policy process with vastly more accountability and technical expertise and would help keep the lobbying in check. They would open the policy process to the public to ensure ample and vigorous discussion. They would force the administration and Congress into a systematic review of the technical knowledge in each field as a basis for policy making, rather than letting misguided policies such as corn-to-ethanol biofuels reap billions in subsidies without public scrutiny.

Currently lobbyists are still allowed to contribute massively to congressional campaigns and to political action committees. The largest lobbying sectors—including finance, health care and transport—have spent billions to promote policies that favor narrow interests over broader public interests. A major step toward reform would be to prohibit campaign contributions by individuals employed by registered lobbying firms. The right of individuals to make campaign contributions would not be infringed, but they would have to make a choice between their lobbying activities and their personal financial contributions to the political process. ■



Jeffrey D. Sachs is director of the Earth Institute at Columbia University (www.earth.columbia.edu).

SCI AM An extended version of this essay is available at **www.ScientificAmerican.com/feb2010**

PHOTOGRAPH BY BRUCE GILBERT/EARTH INSTITUTE; ILLUSTRATION BY MATT COLLINS

Cultivate Your Garden

How a lack of control leads to superstition and what can be done about it

BY MICHAEL SHERMER

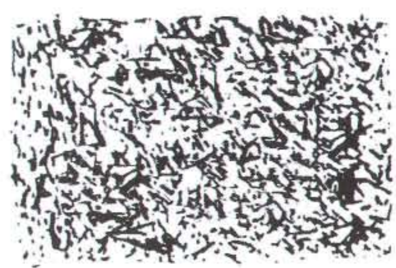
Imagine a time in your life when you felt out of control—anything from getting lost to losing a job. Now look at the top illustration on this page. What do you see? Such a scenario was presented to subjects in a 2008 experiment by Jennifer Whitson of the University of Texas at Austin and her colleague Adam Galinsky of Northwestern University. Their study, entitled "Lacking Control Increases Illusory Pattern Perception," was published in *Science*.

Defining "illusory pattern perception" (what I call "patternicity") as "the identification of a coherent and meaningful interrelationship among a set of random or unrelated stimuli ... (such as the tendency to perceive false correlations, see imaginary figures, form superstitious rituals, and embrace conspiracy beliefs, among others)," the researchers' thesis was that "when individuals are unable to gain a sense of control objectively, they will try to gain it perceptually." As Whitson explained the psychology to me, "Feelings of control are essential for our well-being—we think clearer and make better decisions when we feel we are in control. Lacking control is highly aversive, so we instinctively seek out patterns to regain control—even if those patterns are illusory."

Whitson and Galinsky sat subjects before a computer screen, telling one group they must guess which of two images embodied an underlying concept the computer had selected. For example, they might see a capital A and a lowercase t colored, underlined, or surrounded by a circle or square. Subjects would then guess at an underlying concept, such as "all capital As are red." There was no actual underlying concept—the computer was programmed to tell the subjects randomly that they were either "correct" or "incorrect." Consequently, they developed a sense of lacking control.

Another group did not receive randomized feedback and so felt more in control. In the second part of the experiment subjects were shown 24 "snowy" photographs, half of which contained hidden images such as a hand, horses, a chair or the planet Saturn [*see illustration at bottom right*], whereas the other half just consisted of grainy random dots. Although nearly everyone saw the hidden figures, subjects in the lack-of-control group saw more figures in the photographs that had no embedded images.

In another experiment Whitson and Galinsky had subjects vividly recall an experience in which they either had full control or lacked control over a situation. The subjects then read scenarios in which the characters' success or failure was preceded by unconnected and superstitious behaviors, such as foot stomping

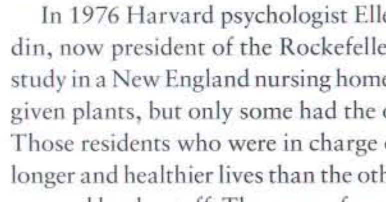


before a meeting where the character wanted to have ideas approved. The subjects were then asked whether they thought the characters' behavior was related to the outcome. Those who had recalled an experience in which they lacked control perceived a significantly greater connection between the two unrelated events than did those who recalled an experience in which they had felt control. Interestingly, the low-control subjects who read a story about an employee who failed to receive a promotion tended to believe that a behind-the-scenes conspiracy was the cause.

In their final experiment Whitson and Galinsky created a sense of lacking control in two groups of subjects, then asked one group to contemplate and affirm their most important values in life—a proven technique for reducing learned helplessness. The researchers then presented those same snowy pictures, finding that those who lacked control but had no opportunity for self-affirmation saw more nonexistent patterns than did those in the self-affirmation condition.

In 1976 Harvard psychologist Ellen J. Langer and Judith Rodin, now president of the Rockefeller Foundation, conducted a study in a New England nursing home in which the residents were given plants, but only some had the opportunity to water them. Those residents who were in charge of watering the plants lived longer and healthier lives than the others, even those given plants watered by the staff. The sense of control had the apparent effect on physical health and well-being.

Perhaps this is what Voltaire meant at the end of *Candide,* in



the title character's rejoinder to Dr. Pangloss's proclamation that "all events are linked up in this best of all possible worlds": "'Tis well said," replied Candide, "but we must cultivate our gardens." ■

Michael Shermer is publisher of Skeptic *magazine (www.skeptic.com) and author of* The Mind of the Market.

PHOTOGRAPH BY BRAD SWONETZ; FROM "LACKING CONTROL INCREASES ILLUSORY PATTERN PERCEPTION," BY JENNIFER A. WHITSON AND ADAM D. GALINSKY, IN *SCIENCE*, VOL. 322; OCTOBER 3, 2008

The Real Promise of Synthetic Biology

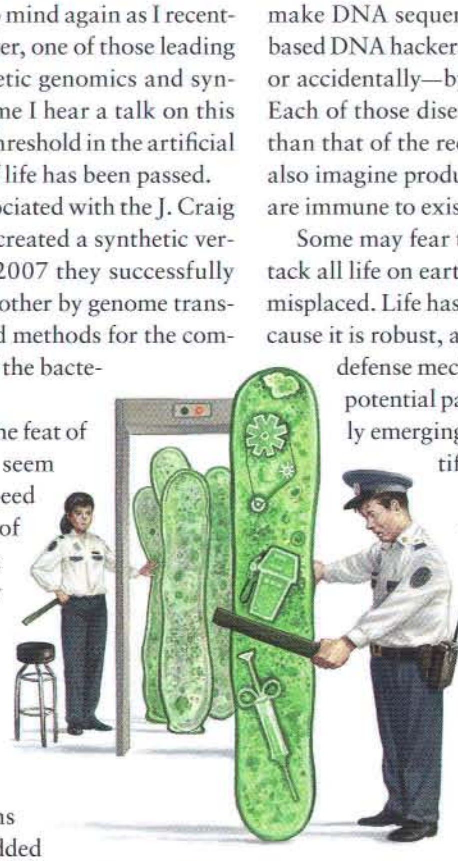
Scientists are closing in on the ability to make life from scratch, with potential consequences both good and bad

BY LAWRENCE M. KRAUSS

I have seen the future, and it is now.

Those words came to mind again as I recently listened to Craig Venter, one of those leading the new areas of synthetic genomics and synthetic biology. Every time I hear a talk on this subject, it seems a new threshold in the artificial manipulation and, ultimately, creation of life has been passed.

Consider just some of the progress associated with the J. Craig Venter Institute. In 2003 its researchers created a synthetic version of the bacteriophage phiX174. In 2007 they successfully transformed one species of bacteria to another by genome transplantation. Most recently, they developed methods for the complete synthetic assembly of the genome of the bacterium *Mycoplasma genitalium*.



The techniques now developed make the feat of sequencing the human genome in 2001 seem prehistoric. Not only have the cost and speed of sequencing evolved faster than those of computer chips, but the ability to use both chemistry and biology to synthesize new complex organisms has undergone a revolution in the past five years. Instructions embedded in synthetic gene sequences can now be implanted in foreign cells and thereby cause those cells to express proteins; those proteins, in turn, build new functioning copies of the life-forms whose instruction manual is in the embedded sequences. Venter calls this cycle "software that creates its own hardware." I expect to hear news soon of the successful creation of the first completely artificial life-form, built from scratch and not alive until the scientists assembled it.

Semiconductor nanotechnology has been heralded for more than a decade, but I believe it will pale beside the ability of biotechnology to transform life and society. Imagine the impact of piggybacking on nature's majesty and designing living systems that can perform tasks not found in nature, from microbes that make gasoline or eat carbon dioxide to create nonbiodegradable plastic building materials to organisms designed to surgically and strategically operate on cancer cells. I expect that within 50 years the world's economy will be driven not by computer-generated information but by biologically generated software.

Of course, as Spiderman would say, with great power comes great responsibility. Hackers now create software viruses that periodically disable huge computer networks. With the ability to make DNA sequences to order has risen the specter of garage-based DNA hackers who might terrorize the world—intentionally or accidentally—by re-creating the Ebola virus or the 1918 flu. Each of those disease organisms has a genetic code far smaller than that of the recently synthesized *M. genitalium*. One could also imagine producing, again perhaps unwittingly, viruses that are immune to existing vaccines.

Some may fear the existence of new life-forms that might attack all life on earth or at least human life. This fear is probably misplaced. Life has survived for more than three billion years because it is robust, and almost no mutations can easily outwit the defense mechanisms built up through eons of exposure to potential pathogens. Venter's argument that new naturally emerging diseases are a far greater threat than new artificial diseases seems relatively compelling.

Nevertheless, there have been, until fairly recently, few checks on the unfettered reproduction of genetic information. As the ability to synthesize more complex biological systems has increased, however, the research community has put in place a voluntary system of restrictions, for example, on the fulfillment of commercial orders for genetic sequences that correspond to portions of potentially lethal organisms. At present, the technological know-how associated with developing synthetic biology laboratories with malice aforethought is probably beyond the means of even sophisticated terrorist networks. Moreover, it is important not to let misplaced fears of Armageddon unduly restrict scientific work with great potential to benefit humankind.

I have always felt that, aside from research that violates universal human mores, when it comes to technological applications, that which can be done will be done. What we need to do is rigorously attempt to anticipate what may be possible so that we can minimize the risks and maximize the benefits. We need to walk into the future, no matter how unnerving, with open eyes if society is to keep pace with technology. ■

Lawrence M. Krauss, a theoretical physicist, commentator and book author, is Foundation Professor and director of the Origins Initiative at Arizona State University (http://krauss.faculty.asu.edu).

PHOTOGRAPH BY JOHN BOSWELL; ILLUSTRATION BY MATT COLLINS

Cloudy with a Chance of Stars

Making a star is no easy thing

By Erick T. Young

KEY CONCEPTS

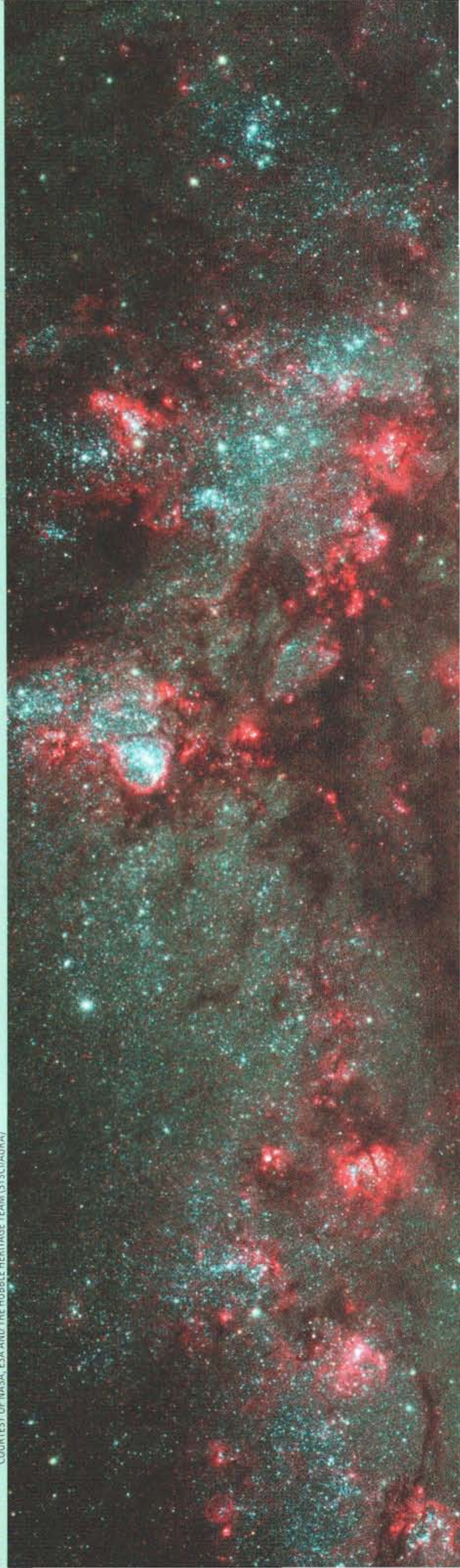
- Although astronomers' theory of star formation has advanced substantially in recent years, it still has serious holes. Stars form out of gaseous clouds that collapse, yet where do those clouds come from and what makes them collapse?
- In addition, standard theory treats stars in isolation, neglecting their interactions and blowback on their natal clouds.
- Astronomers are making progress on filling in these gaps. For instance, they have seen how massive stars can trigger the collapse of clouds and how newborn stars fling one another into deep space.

—The Editors

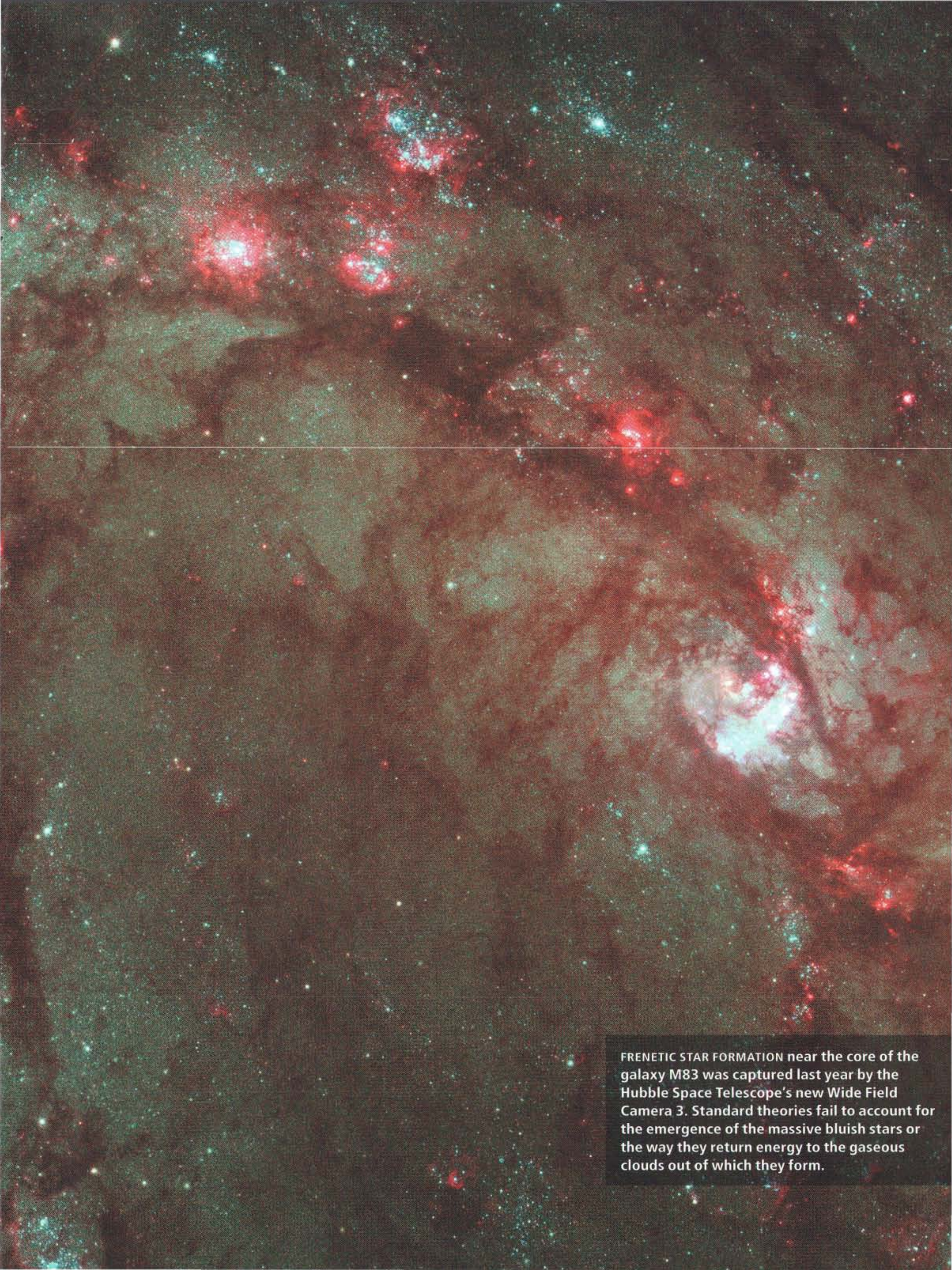
If there is anything you think astronomers would have figured out by now, it is how stars form. The basic idea for how stars form goes back to Immanuel Kant and Pierre-Simon Laplace in the 18th century, and the details of how they shine and evolve were worked out by physicists in the first half of the 20th century. Today the principles that govern stars are taught in middle school, and exotica such as dark matter dominate the headlines. It might seem that star formation is a problem that has been solved. But nothing could be further from the truth. The birth of stars remains one of the most vibrant topics in astrophysics today.

In the simplest terms, the process represents the victory of gravity over pressure. It starts with a vast cloud of gas and dust floating in interstellar space. If the cloud—or, more often, a dense part of such a cloud called a core—is cool and dense enough, the inward pull of its gravity overpowers the outward push of gaseous pressure, and it begins to collapse under its own weight. The cloud or core becomes ever denser and hotter, eventually sparking nuclear fusion. The heat generated by fusion increases the internal pressure and halts the collapse. The newborn star settles into a dynamic equilibrium that can last millions to trillions of years.

The theory is self-consistent and matches a



COURTESY OF NASA, ESA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA)

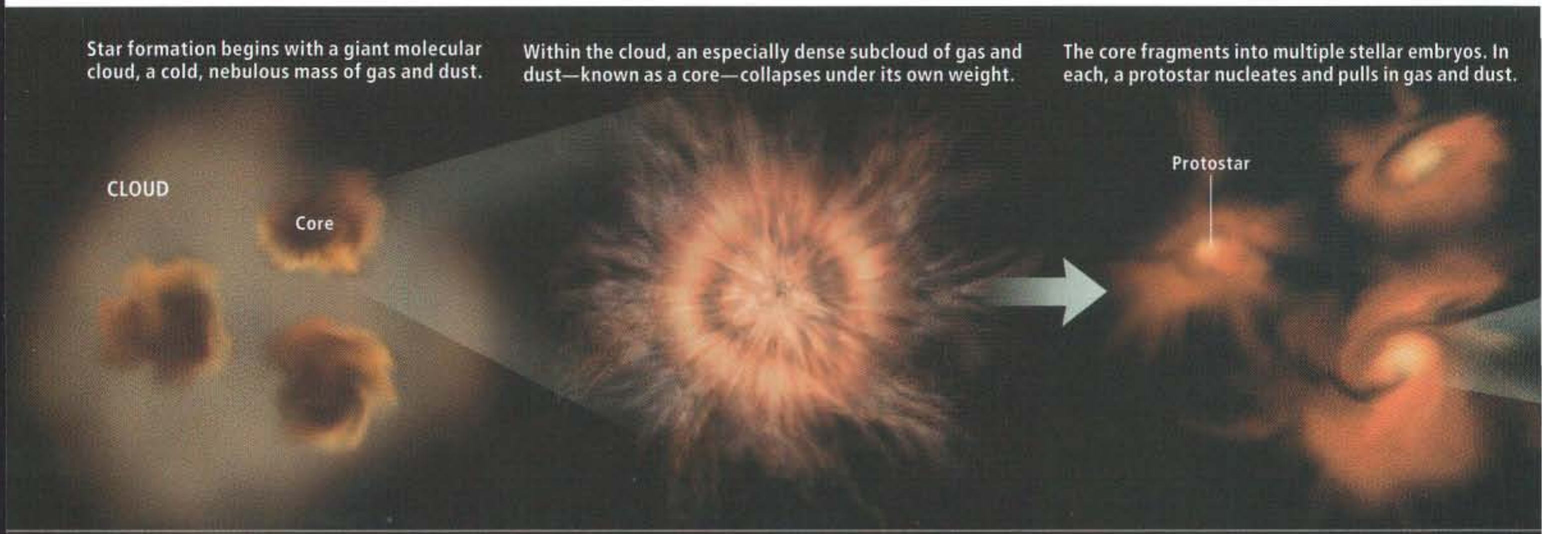


FRENETIC STAR FORMATION near the core of the galaxy M83 was captured last year by the Hubble Space Telescope's new Wide Field Camera 3. Standard theories fail to account for the emergence of the massive bluish stars or the way they return energy to the gaseous clouds out of which they form.

[STANDARD THEORY]

A Star Is Born—With Difficulty

The standard theory of star formation neatly explains isolated low- to medium-mass stars but leaves many conceptual gaps.



PROBLEM #1: Where does the cloud come from? A mixture of material produced in the big bang or ejected from stars must somehow coagulate.

PROBLEM #2: Why does the core collapse? The model does not specify how the balance of forces that stabilizes the cloud is disrupted.

PROBLEM #3: How do the embryos affect one another? The standard theory of star formation treats stars in isolation.

[THE AUTHOR]

Erick T. Young got his start in astronomy at age 10 by building a telescope out of a cardboard tube. He is now director of Science Mission Operations for the Stratospheric Observatory for Infrared Astronomy (SOFIA). Young was an astronomer at Steward Observatory of the University of Arizona from 1978 until 2009. He has been on the science teams for nearly every major infrared space facility, including the Infrared Astronomical Satellite, the Infrared Space Observatory, the NICMOS camera and the Wide Field Camera 3 on the Hubble Space Telescope, the Spitzer Space Telescope and the upcoming James Webb Space Telescope.

growing body of observations. Yet it is far from complete. Every sentence of the above paragraph cries out for explanation. Four questions, in particular, trouble astronomers. First, if the dense cores are the eggs of stars, where are the cosmic chickens? The clouds must themselves come from somewhere, and their formation is not well understood. Second, what causes the core to begin collapsing? Whatever the initiation mechanism is, it determines the rate of star formation and the final masses of stars.

Third, how do embryonic stars affect one another? The standard theory describes individual stars in isolation; it does not say what happens when they form in close proximity, as most stars do. Recent findings suggest that our own sun was born in a cluster, which has since dispersed [see "The Long-Lost Siblings of the Sun," by Simon F. Portegies Zwart; SCIENTIFIC AMERICAN, November 2009]. How does growing up in a crowded nursery differ from being an only child?

Fourth, how do very massive stars manage to form at all? The standard theory works well for building up stars of as much as 20 times the mass of the sun but breaks down for bigger ones, whose tremendous luminosity should blow away the cloud before the nascent star can accumulate the requisite mass. What is more, massive stars blast their surroundings with ultraviolet radiation, high-velocity outflows and supersonic shock waves. This energy feedback disrupts the cloud, yet the standard theory does not take it into account.

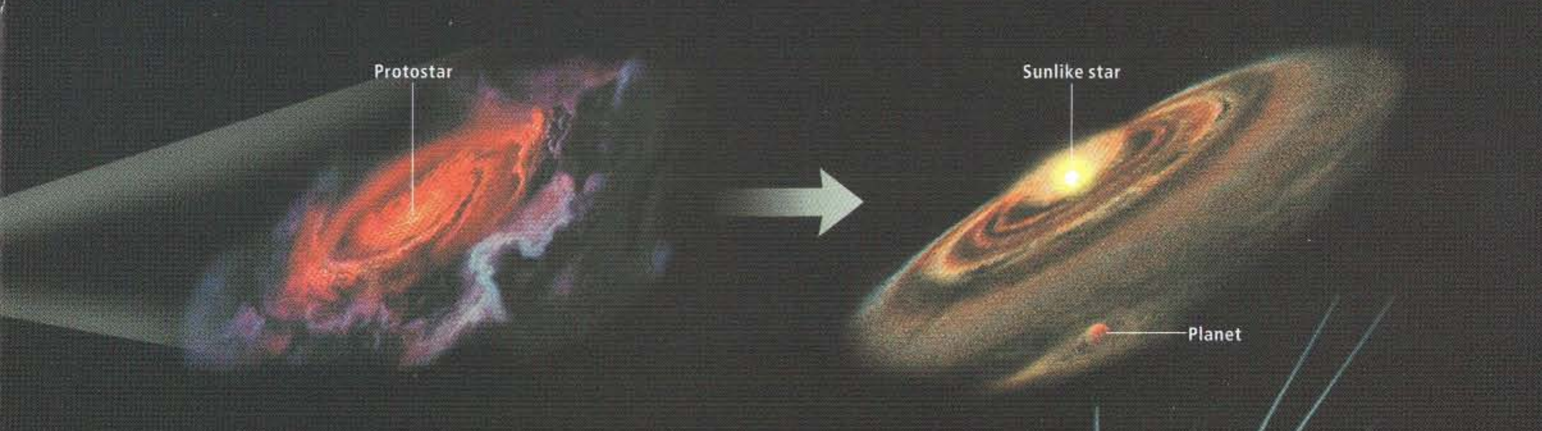
The need to address these shortcomings has become increasingly pressing. Star formation underlies almost everything else in astronomy, from the rise of galaxies to the genesis of planets. Without understanding it, astronomers cannot hope to dissect distant galaxies or make sense of the planets being discovered beyond our solar system. Although final answers remain elusive, a common theme is emerging: a more sophisticated theory of star formation must consider the environment of a fledgling star. The final state of the new star depends not only on initial conditions in the core but also on the subsequent influences of its surroundings and its stellar neighbors. It is nature versus nurture on a cosmic scale.

Swaddled in Dust

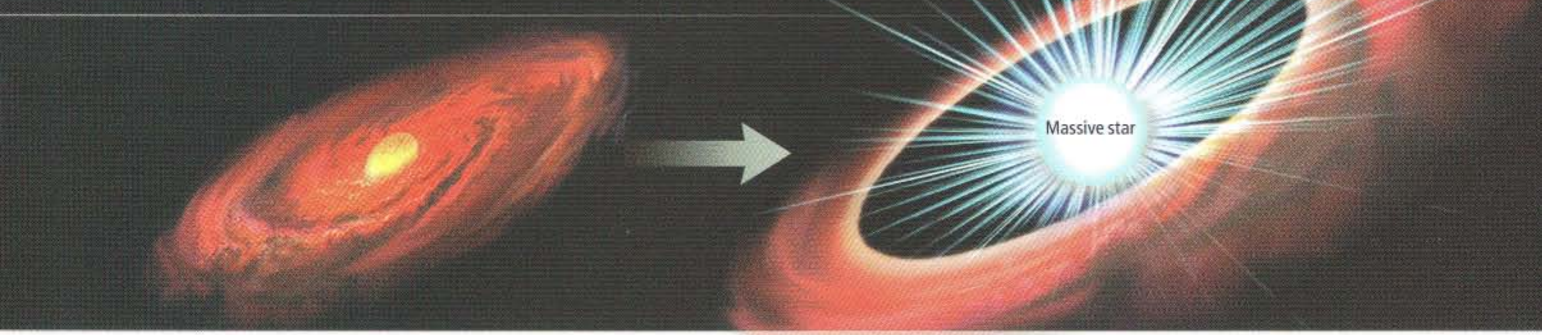
If you look at the sky from a dark site, far from city lights, you can see the Milky Way arching over you, its diffuse stream of light interrupted by dark patches. These are interstellar clouds. The dust particles in them block starlight and make them opaque to visible light.

COURTESY OF ERICK T. YOUNG (Young); DON DIXON (star formation)

The protostar shrinks in size, increases in density and officially becomes a star when nuclear fusion begins in its core. Planets emerge from the leftover material swirling around it.



PROBLEM #4: How do massive stars form?
Nascent stars above 20 solar masses are so luminous that they would be expected to disrupt their own formation, as well as that of nearby stars.



Consequently, those of us who seek to observe star formation face a fundamental problem: stars cloak their own birth. The material that goes into creating a star is thick and dark; it needs to become dense enough to initiate nuclear fusion but has not done so yet. Astronomers can see how this process begins and how it ends, but what comes in the middle is inherently hard to observe, because much of the radiation comes out at far-infrared and submillimeter wavelengths where the astronomer's toolbox is relatively primitive compared with other parts of the spectrum.

Astronomers think that stars' natal clouds arise as a part of the grand cycle of the interstellar medium, in which gas and dust circulate from clouds to stars and back again. The medium consists primarily of hydrogen; helium makes up about one quarter by mass, and all the other elements amount to a few percent. Some of this material is primordial matter barely disturbed since the first three minutes of the big bang; some is cast off by stars during their lifetimes; and some is the debris of exploded stars. Stellar radiation breaks any molecules of hydrogen into their constituent atoms [see "The Gas between the Stars," by Ronald J. Reynolds; Scientific American, January 2002].

Initially the gas is diffuse, with about one hydrogen atom per cubic centimeter, but as it cools it coagulates into discrete clouds, much as water vapor condenses into clouds in Earth's atmosphere. The gas cools by radiating heat, but the process is not straightforward, because there are only a limited number of ways for the heat to escape. The most efficient turns out to be far-infrared emission from certain chemical elements, such as the radiation emitted by ionized carbon

[PROBLEM #1]

The Dark Origins of Interstellar Clouds

Astronomers have gradually identified the stages by which clouds coalesce from diffuse interstellar gas and become progressively denser. The stage immediately prior to protostar formation is represented by so-called infrared dark clouds. Opaque even to infrared light, they show up as black streaks in this image from the Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE), performed by the Spitzer Space Telescope. Their size and mass are just right for forming stars.

at a wavelength of 158 microns. Earth's lower atmosphere is opaque at these wavelengths, so they must be observed using space-based observatories such as Herschel Space Observatory, launched last year by the European Space Agency, or telescopes mounted in airplanes, such as the Stratospheric Observatory for Infrared Astronomy (SOFIA).

As the clouds cool, they become denser. When they reach about 1,000 atoms per cubic centimeter, they are thick enough to block ultraviolet radiation from the surrounding galaxy. Hydrogen atoms can then combine into molecules through a complicated process involving dust grains. Radio observations have shown that molecular clouds contain compounds ranging from hydrogen (H_2) up to complex organics, which may have provided the wherewithal for life on Earth [see "Life's Far-Flung Raw Materials," by Max P. Bernstein, Scott A. Sandford and Louis J. Allamandola; SCIENTIFIC AMERICAN, July 1999]. Beyond this stage, however, the trail goes cold. Infrared observations have revealed nascent stars deeply embedded in dust but have trouble seeing the earliest steps leading from molecular cloud to these protostars.

The situation for the very earliest stages of star formation began to change in the mid-1990s, when the Midcourse Space Experiment and the Infrared Space Observatory discovered clouds so dense (more than 10,000 atoms per cubic centimeter) that they are opaque even to the thermal infrared wavelengths that usually penetrate dusty regions. These so-called infrared dark clouds are much more massive (100 to 100,000 times the mass of the sun) than clouds that had been previously discovered at optical wavelengths. Over the past several years two teams have used the Spitzer Space Telescope to make a comprehensive survey of them: the Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE) led by Edward B. Churchwell of the University of Wisconsin–Madison and the MIPSGAL survey led by Sean Carey of the Spitzer Science Center. These clouds appear to be the missing link between molecular clouds and protostars.

In fact, dark clouds and dense cores could represent the crucial formative stage of stars when their masses are determined. The clouds come in a range of masses; small ones are more common than large ones. This distribution of masses closely mimics that of stars—except that the clouds are systematically three times more massive than stars, suggesting that only one third of the mass of a cloud ends up in the newborn star. The rest is somehow lost to space.

Whether this similarity in distributions is causal or just coincidental remains to be proved. Whatever sets the mass of a star determines its entire life history: whether it is a massive star that dies young and explodes catastrophically or a more modest star that lives longer and goes more gently into that good night.

OTHER WAYS THAT STARS MYSTIFY

How fast do stars form? That is another question with which astronomers have struggled. The crucial choke point is the final stage of collapse, after a protostar has nucleated but before it has bulked up by accreting gas. A team led by Neal J. Evans II of the University of Texas at Austin has observed nearby star-forming complexes with the Spitzer Space Telescope and found that accretion occurs at a very unsteady rate. The star rapidly builds up to half its final mass, but its growth then slows; it takes more than 10 times as long to accumulate the rest. The overall process takes much longer than previously estimated.

Another problem is that the gas in molecular clouds is highly turbulent and moving at supersonic velocities. What stirs it up? Embryonic stars themselves might be responsible. Almost all protostars spray out high-velocity jets [see "Fountains of Youth: Early Days in the Life of a Star," by Thomas P. Ray; SCIENTIFIC AMERICAN, August 2000].

What Pulled the Trigger?

Astronomers are also making some progress on the second major unresolved problem, which is what causes a cloud or core to collapse. In the standard model of star formation, a core begins in beautiful equilibrium, with gravity and external pressure balanced by internal thermal, magnetic or turbulent pressure. Collapse begins when this balance is upset in favor of gravity.

But what triggers the imbalance? Astronomers have proposed many different ways. An outside force such as a supernova explosion might compress the cloud, or the internal pressure might ebb as heat or magnetic fields dissipate.

Charles Lada of the Harvard-Smithsonian Center for Astrophysics (CfA), João Alves of the European Southern Observatory (ESO) and their co-workers have argued for the slow dissipation of thermal support. By mapping molecular clouds at millimeter and submillimeter wavelengths, which straddle the radio and infrared bands, they have been able to identify a large number of relatively quiescent, isolated cores in nearby clouds. Some show evidence of slow inward motions and may be on their way to making stars. An excellent example is Barnard 335, located in the constellation Aquila. Its density structure is just what would be expected if the cloud's thermal pressure were nearly in equilibrium with external pressure. An infrared source in the center may be an early-stage protostar, suggesting that the balance recently tilted in favor of collapse.

Other studies find evidence for external triggering. Thomas Preibisch of the Max Planck Institute for Radio Astronomy in Bonn and his collaborators have showed that widely distributed stars in the Upper Scorpius region all formed nearly in unison. It would be quite a coincidence for the internal pressure of different cores to dissipate at the same time. A likelier explanation is that a shock wave set off by a supernova swept through the region and induced the cores to collapse. The evidence is ambiguous, however, because massive stars disrupt their birthplaces, making it difficult to reconstruct the conditions under which they formed. Another limitation has been the difficulty of seeing lower-mass stars (which are dimmer) to confirm that they, too, formed in synchrony.

Spitzer has made progress on these questions. Lori Allen of the National Optical Astronomy Observatory, Xavier P. Koenig of the CfA and their collaborators have discovered a striking example of external triggering in a region of the galaxy known as W5 [*see box at right*]. Their image shows young protostars embedded in dense pockets of gas that have been compressed by radiation from an earlier generation of stars. Because compression is a rapid process, these widely scattered objects must have formed almost simultaneously. In short, the triggering of star formation is not an either-or situation, as once thought. It is case of "all of the above."

Life in a Stellar Nursery

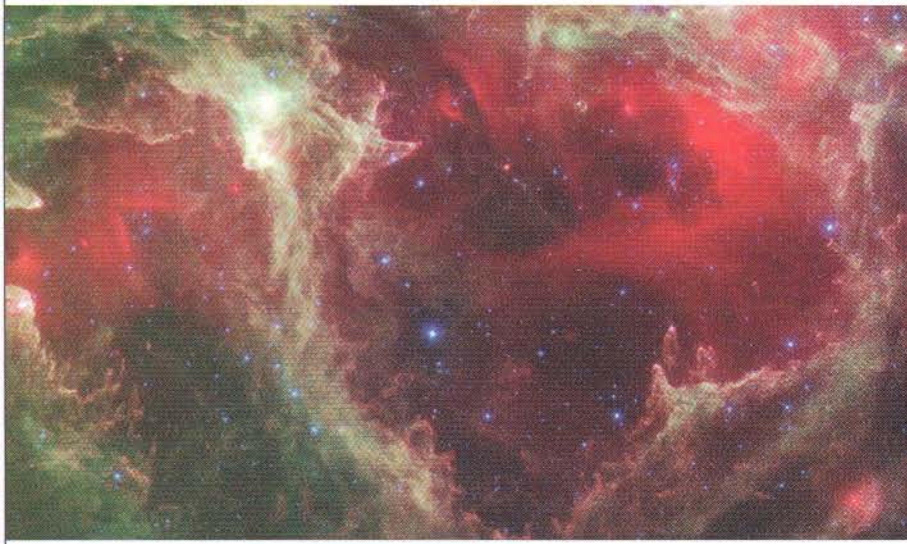
Leaving aside the above deficiencies, the standard model explains observations of isolated star-forming cores fairly well. But many, perhaps most, stars form in clusters, and the model does not account for how this congested environment affects their birth. In recent years researchers have developed two competing theories to fill in this gap. The great advance in the computing power available for simulations has been crucial in honing these theories. Observations, notably by Spitzer, are helping astronomers to decide between them.

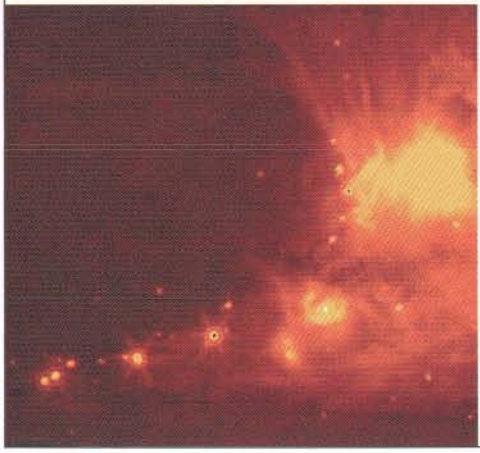
In one, interactions between adjacent cores become important. In the extreme version, many very small protostars form, move rapidly through the cloud and compete to accrete the remaining

[PROBLEM #2]

The Onset of Collapse

Astronomy textbooks are vague as to how clouds become destabilized and collapse. New Spitzer infrared images reveal that nearby massive stars are often responsible.





▲ In the W5 region of the galaxy, massive stars (which look bluish) have cleared out a cavity in a molecular cloud. On the rim of the cavity are protostars (embedded in whitish and pinkish gas) that are all roughly the same age, indicating that their formation was triggered by the massive stars; other processes would not have been so synchronized.

◄ In the cluster NGC 2068, protostars are lined up like pearls on a string. Though widely scattered, they have formed almost simultaneously, and again the most likely culprit is a group of nearby massive stars.

COURTESY OF NASA, JPL/CALTECH AND HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS (*W5*); COURTESY OF ERICK T. YOUNG AND NASA (*NGC 2068*)

INFRARED 101

The interstellar clouds where stars form look like black splotches in visible light but come alive at infrared and radio wavelengths.

Infrared radiation has a wavelength of one to 1,000 microns, or one millimeter. Matter with temperatures between three and 3,000 kelvins emits radiation that peaks in this band.

Near-infrared radiation is the short-wavelength end of this range, roughly one to five microns. It is mostly starlight that has been modestly attenuated by dust.

Mid- and far-infrared radiation extends up to about 300 microns. Dust emission is the primary source. It is hard to see from the ground because Earth itself emits in this band and because Earth's atmosphere blocks most of the celestial emission.

Submillimeter radiation, the band from 300 to 1,000 microns, is a good place to see cold interstellar material.

Radio waves are everything longer than that.

gas. Some grow much bigger than others, and the losers may be ejected from the cluster altogether, creating a class of stellar runts that roam the galaxy. This picture, called competitive accretion, has been championed by Ian Bonnell of the University of St. Andrews, Matthew Bate of the University of Exeter, and others.

In the alternative model, the main external influence is not interactions among cores but turbulence within the gas. The turbulence helps to trigger collapse, and the size distribution of stars reflects the spectrum of turbulent motions rather than a later competition for material. This turbulent-core model has been developed by Christopher McKee of the University of California, Berkeley, Mark Krumholz of the University of California, Santa Cruz, and others.

Observations seem to favor the turbulent-core model [see "The Mystery of Brown Dwarf Origins," by Subhanjoy Mohanty and Ray Jayawardhana; SCIENTIFIC AMERICAN, January 2006], but the competitive-accretion model may be important in regions of particularly high stellar density. One very interesting case is the famous Christmas Tree Cluster (NGC 2264) in the constellation Monoceros. In visible light, this region shows a number of bright stars and an abundance of dust and gas—hallmarks of star formation. Spitzer observations have revealed a dense embedded cluster with stars in various stages of development. This cluster provides a snapshot of precisely those stages when either turbulence or competitive accretion would leave its mark.

The youngest stars, identified as those with the largest proportion of emission at long wavelengths, are clumped in a tight group. Paula S. Teixeira, now at ESO, and her collaborators have shown that they are spaced roughly every 0.3 light-year. This regular pattern is just what would be expected if dense cores were gravitationally collapsing out of the general molecular cloud, suggesting that the initial conditions in the cloud are what determine the road to collapse. And yet, even though the observations support the turbulent model, the images have good enough resolution to tell that some of the supposed protostars are not single objects but compact groups of objects. One consists of 10 sources within a 0.1-light-year radius. These objects have such a high density that competitive accretion must be taking place, at least on a small scale.

Therefore, as with triggering mechanisms, the effect of the stellar environment is not an either-or choice. Both turbulence and competitive accretion can operate, depending on the situation. Nature seems to take advantage of every possible way to make a star.

Supersize This Star

Massive stars are rare and short-lived, but they play a very important role in the evolution of galaxies. They inject energy into the interstellar medium via both radiation and mass outflows and, at the end of their lives, can explode as supernovae, returning matter enriched in heavy elements. The Milky Way is riddled with bubbles and supernova remnants created by such stars. Yet the standard theory has trouble explaining their formation. Once a protostar reaches a threshold of about 20 solar masses, the pressure exerted by its radiation should overpower gravity and prevent it from growing any bigger. In addition to the radiation pressure, the winds that so massive a star generates disperse its natal cloud, further limiting its growth as well as interfering with the formation of nearby stars.

Recent theoretical work by Krumholz and his collaborators offers one way out of this problem. Their three-dimensional simulations show stellar growth in all its unexpected intricacy. The inflow of material can become quite non-

[PROBLEM #3]

Life in a Crowded Nursery

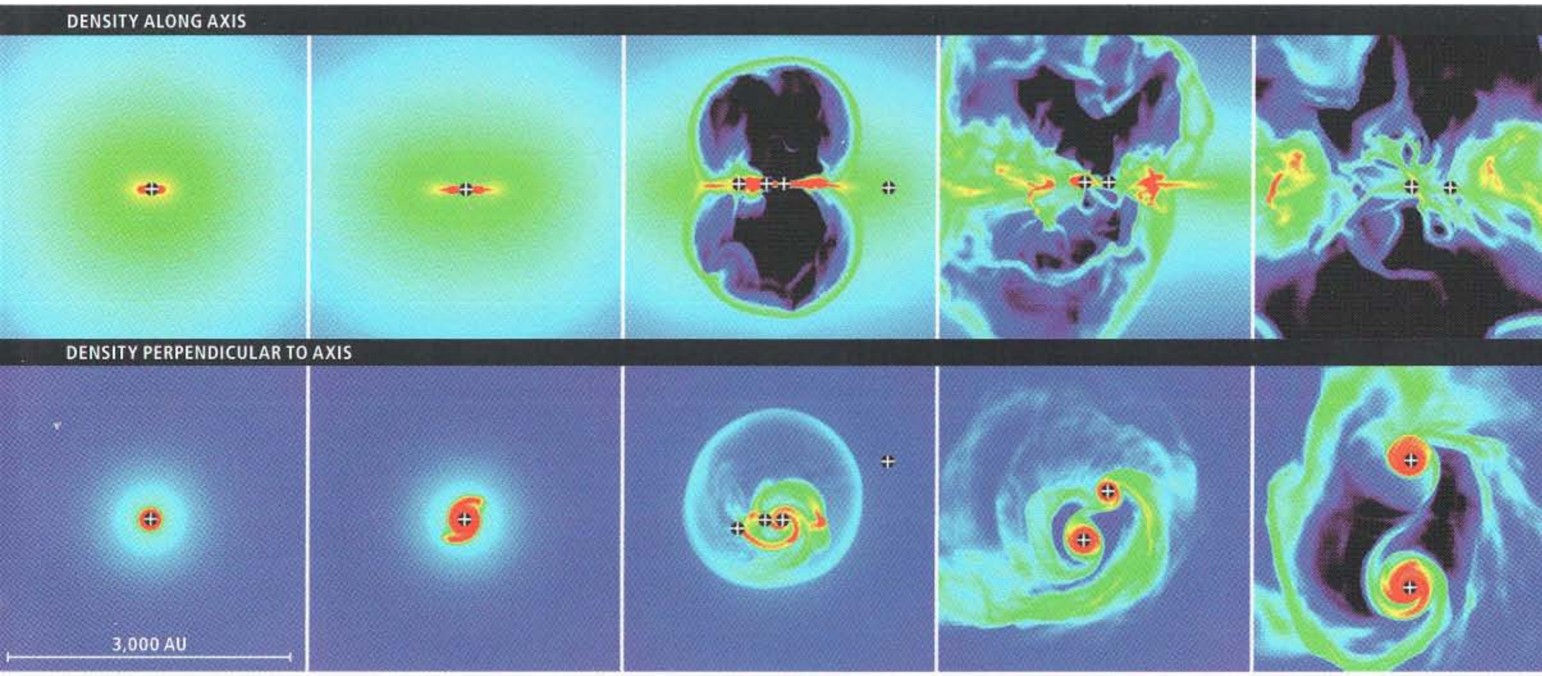
Contradicting the assumptions made in the standard model of star formation, newborn stars can interfere with one another's formation. Spitzer has found an example in the Christmas Tree Cluster (NGC 2264), which contains a dense cluster of stars of varying ages. At high resolution, some of the youngest "stars" turn out to be tight groupings of protostars—as many as 10 of them within a radius of 0.1 light-year, close enough to affect one another.

COURTESY OF NASA, JPL/CALTECH AND PAULA S. TEIXEIRA *Harvard-Smithsonian Center for Astrophysics*

[PROBLEM #4]

Breaking through the Mass Ceiling

Recent computer simulations of star formation show that a massive star is able to reach a seemingly impossible size because it does not grow uniformly. Radiation emitted by the protostar pushes gas away, creating giant voids (bubbles) within the gas, but does not completely choke off the inward flow of gas, because material collects into filaments in the interstices of these voids.



17,500 YEARS: A protostar has formed, and gas falls in nearly uniformly. Gravitational potential energy released by the descent of the gas causes it to glow.

25,000 YEARS: When the protostar has grown to about 11 solar masses, the disk around it becomes gravitationally unstable and develops a spiral shape.

34,000 YEARS: When the protostar exceeds 17 solar masses, radiation pushes gas out, creating bubbles. But gas still flows in around them. Smaller protostars form.

41,700 YEARS: One of the small protostars grows faster than the central one and soon rivals it in size. Accretion is not only uneven in space but also unsteady in time.

55,900 YEARS: Simulation ends as the central star reaches 42 solar masses and its companion 29. Some 28 solar masses of gas remain and will probably fall in eventually.

FROM "THE FORMATION OF MASSIVE STAR SYSTEMS BY ACCRETION," BY MARK R. KRUMHOLZ ET AL., IN *SCIENCE*, VOL 323; JANUARY 15, 2009

uniform; dense regions alternate with bubbles where the starlight streams out. Therefore, the radiation pressure may not pose an obstacle to continued growth after all. The dense infalling material also readily forms companion stars, explaining why massive stars are seldom alone. Observers are now looking for confirmation using Spitzer surveys of massive star-forming regions. But verifying the model will be tricky. The rarity and short lives of these stars make them hard to catch in the act of forming.

Fortunately, new facilities will soon help with this and the other questions posed by star formation. Herschel and SOFIA, a Boeing 747 that flies above 99 percent of the obscuring water vapor of Earth's atmosphere, will observe the far-infrared and submillimeter wavelengths where star formation is easiest to see. They have the spatial and spectral resolution needed to map the velocity pattern in interstellar clouds. At longer wavelengths, the Atacama Large Millimeter Array (ALMA), now under construction in the Chilean Andes, will allow mapping of individual protostars in exquisite detail.

With new observations, astronomers hope to trace the complete life cycle of the interstellar medium from atomic clouds to molecular clouds to prestellar cores to stars and ultimately back into diffuse gas. They also hope to observe star-forming disks with enough angular resolution to be able to trace the infall of material from the cloud, as well to compare the effects of different environments on stellar birth.

The answers will ripple out into other domains of astrophysics. Everything we see—galaxies, interstellar clouds, stars, planets, people—has been made possible by star formation. Our current theory of star formation is not a bad one, but its gaps leave us unable to explain many of the most important aspects of today's universe. And in those gaps we see that star formation is a richer process than anyone ever predicted. ■

➡ MORE TO EXPLORE

Spitzer and Magellan Observations of NGC 2264: A Remarkable Star-Forming Core near IRS-2. Erick T. Young et al. in *Astrophysical Journal*, Vol. 642, No. 2, pages 972–978; May 10, 2006. **arxiv.org/abs/astro-ph/0601300**

The Formation of Massive Star Systems by Accretion. Mark R. Krumholz et al. in *Science*, Vol. 323, pages 754–757; January 15, 2009. **arxiv.org/abs/0901.3157**

The Violent, Mysterious Dynamics of Star Formation. Adam Frank in *Discover*; February 2009. Available at **http://discovermagazine.com/2009/feb/26-violent-mysterious-dynamics-of-star-formation**

The Naked Truth

Recent findings lay bare the origins of human hairlessness—and hint that naked skin was a key factor in the emergence of other human traits

BY NINA G. JABLONSKI

KEY CONCEPTS

- Humans are the only primate species that has mostly naked skin.
- Loss of fur was an adaptation to changing environmental conditions that forced our ancestors to travel longer distances for food and water.
- Analyses of fossils and genes hint at when this transformation occurred.
- The evolution of hairlessness helped to set the stage for the emergence of large brains and symbolic thought.

—The Editors

Among primates, humans are unique in having nearly naked skin. Every other member of our extended family has a dense covering of fur—from the short, black pelage of the howler monkey to the flowing copper coat of the orangutan—as do most other mammals. Yes, we humans have hair on our heads and elsewhere, but compared with our relatives, even the hairiest person is basically bare.

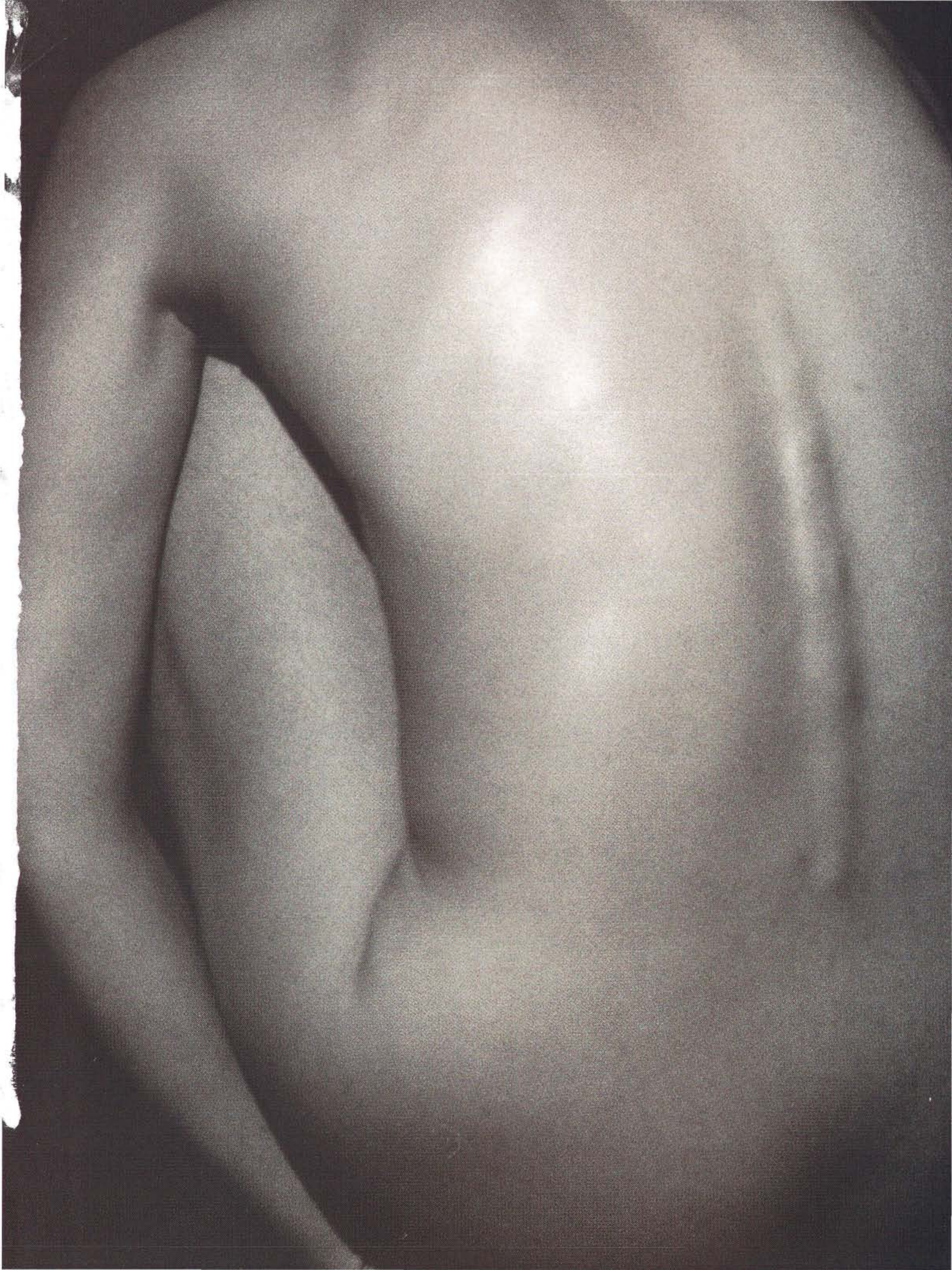
How did we come to be so denuded? Scholars have pondered this question for centuries. Finding answers has been difficult, however: most of the hallmark transitions in human evolution—such as the emergence of upright walking—are recorded directly in the fossils of our predecessors, but none of the known remains preserves impressions of human skin. In recent years, though, researchers have realized that the fossil record does contain indirect hints about our transformation from hirsute to hairless. Thanks to these clues and insights gleaned over the past decade from genomics and physiology, I and others have pieced together a compelling account of why and when humans shed their fur. In addition to explaining a very peculiar quirk of our appearance, the scenario suggests that naked skin itself played a crucial role in the evolution of other characteristic human traits, including our large brain and dependence on language.

Hairy Situations

To understand why our ancestors lost their body hair, we must first consider why other species have coats in the first place. Hair is a type of body covering that is unique to mammals. Indeed, it is a defining characteristic of the class: all mammals possess at least some hair, and most of them have it in abundance. It provides insulation and protection against abrasion, moisture, damaging rays of sunlight, and potentially harmful parasites and microbes. It also works as camouflage to confuse predators, and its distinctive patterns allow members of the same species to recognize one another. Furthermore, mammals can use their fur in social displays to indicate aggression or agitation: when a dog "raises its hackles" by involuntarily elevating the hairs on its neck and back, it is sending a clear signal to challengers to stay away.

Yet even though fur serves these many important purposes, a number of mammal lineages have evolved hair that is so sparse and fine as to serve no function. Many of these creatures live underground or dwell exclusively in the water.

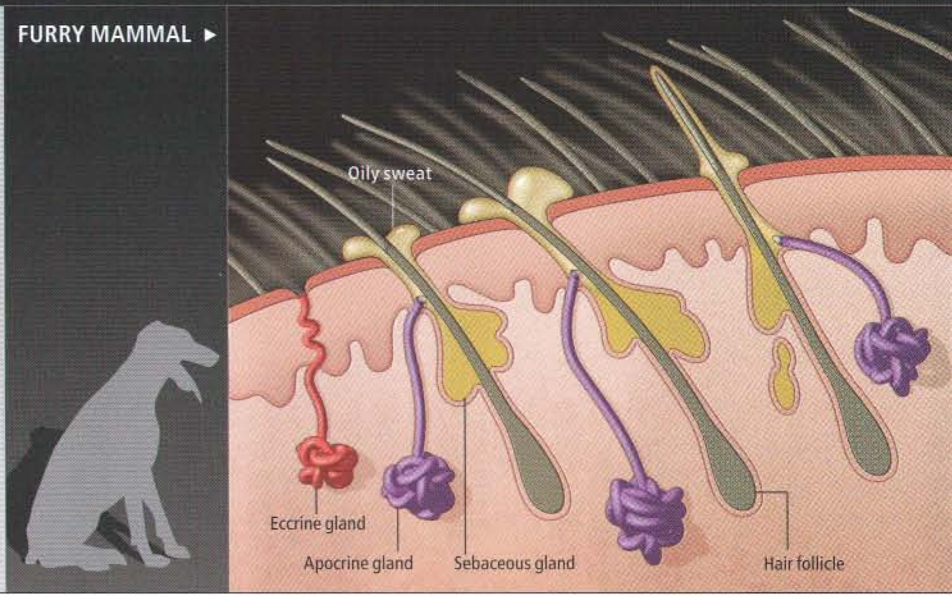
DORIT THIES



[BENEFITS OF HAIRLESSNESS]

FURRY VS. NAKED

Naked human skin is better at ridding the body of excess heat than is fur-covered skin. Mammals possess three types of glands for the purpose: apocrine, eccrine and sebaceous. In most mammals the outermost layer of the skin, known as the epidermis, contains an abundance of apocrine glands. These glands cluster around hair follicles and coat the fur in a lather of oily sweat. Evaporation of this sweat, which cools the animal by drawing heat away from the skin, occurs at the surface of the fur. But the more the animal perspires, the less effectively it eliminates heat because the fur becomes matted, hampering evaporation. In the human epidermis, in contrast, eccrine glands predominate. These glands reside close to the skin surface and discharge thin, watery sweat through tiny pores. In addition to evaporating directly from the skin surface, this eccrine sweat vaporizes more readily than apocrine sweat, thus permitting improved cooling.



In subterranean mammals, such as the naked mole rat, hairlessness evolved as a response to living in large underground colonies, where the benefits of hair are superfluous because the animals cannot see one another in the dark and because their social structure is such that they simply huddle together for warmth. In marine mammals that never venture ashore, such as whales, naked skin facilitates long-distance swimming and diving by reducing drag on the skin's surface. To compensate for the lack of external insulation, these animals have blubber under the skin. In contrast, semiaquatic mammals—otters, for example—have dense, waterproof fur that traps air to provide positive buoyancy, thus decreasing the effort needed to float. This fur also protects their skin on land.

The largest terrestrial mammals—namely, elephants, rhinoceroses and hippopotamuses—also evolved naked skin because they are at constant risk of overheating. The larger an animal is, the less surface area it has relative to overall body mass and the harder it is for the creature to rid its body of excess heat. (On the flip side, mice and other small animals, which have a high surface-to-volume ratio, often struggle to retain sufficient heat.) During the Pleistocene epoch, which spans the time between two million and 10,000 years ago, the mammoths and other relatives of modern elephants and rhinoceroses were "wooly" because they lived in cold environments, and external insulation helped them conserve body heat and lower their food intake. But all of today's megaherbivores live in sweltering conditions, where a fur coat would be deadly for beasts of such immense proportions.

Human hairlessness is not an evolutionary adaptation to living underground or in the water—the popular embrace of the so-called aquatic ape hypothesis notwithstanding [*see box on opposite page*]. Neither is it the result of large body size. But our bare skin is related to staying cool, as our superior sweating abilities suggest.

Sweating It Out

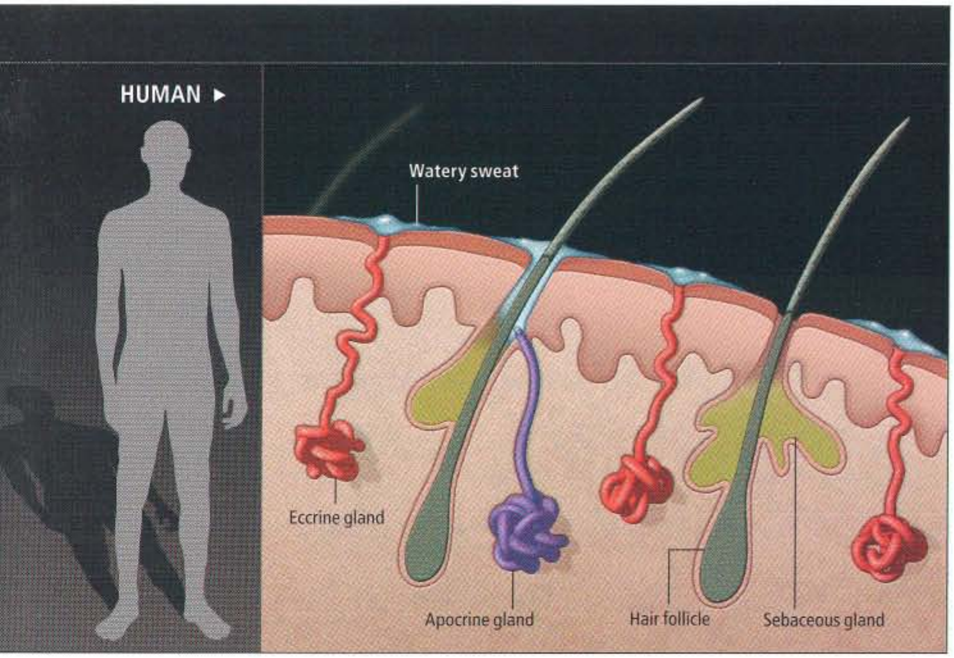
Keeping cool is a big problem for many mammals, not just the giant ones, especially when they live in hot places and generate abundant heat from prolonged walking or running. These animals must carefully regulate their core body temperature because their tissues and organs, specifically the brain, can become damaged by overheating.

Mammals employ a variety of tactics to avoid burning up: dogs pant, many cat species are most active during the cooler evening hours, and many antelopes can off-load heat from the blood in their arteries to blood in small veins that has been cooled by breathing through the nose. But for primates, including humans, sweating is the primary strategy. Sweating cools the body through the production of liquid on the skin's surface that then evaporates, drawing heat energy away from the skin in the process. This whole-body cooling mechanism operates according to the same principle as an evaporative cooler (also known as a swamp cooler), and it is highly effective in preventing the dangerous overheat-

[THE AUTHOR]

Nina G. Jablonski is head of the anthropology department at Pennsylvania State University. Her research focuses on the natural history of human skin, the origin of bipedalism, the evolution and biogeography of Old World monkeys, and the paleoecology of mammals that lived during the past two million years. She has conducted fieldwork in China, Kenya and Nepal. This is her second article for *Scientific American*. The first, co-authored with George Chaplin and published in October 2002, described the evolution of human skin color.

COURTESY OF DONG LIN (*Jablonski*); TAMI TOLPA (*skin cross sections*); JEN CHRISTIANSEN (*dog and human*)



ing of the brain, as well as of other body parts.

Not all sweat is the same, however. Mammalian skin contains three types of glands—sebaceous, apocrine and eccrine—that together produce sweat. In most species, sebaceous and apocrine glands are the dominant sweat glands and are located near the base of hair follicles. Their secretions combine to coat hairs with an oily, sometimes foamy, mixture (think of the lather a racehorse generates when it runs). This type of sweat helps to cool the animal. But its ability to dissipate heat is limited. G. Edgar Folk, Jr., of the University of Iowa and his colleagues showed nearly two decades ago that the effectiveness of cooling diminishes as an animal's coat becomes wet and matted with this thick, oily sweat. The loss of efficiency arises because evaporation occurs at the surface of the fur, not at the surface of the skin itself, thus impeding the transfer of heat. Under conditions of duress, heat transfer is inefficient, requiring that the animal drink large amounts of water, which may not be readily available. Fur-covered mammals forced to exercise energetically or for prolonged periods in the heat of day will collapse from heat exhaustion.

Humans, in addition to lacking fur, possess an extraordinary number of eccrine glands—between two million and five million—that can produce up to 12 liters of thin, watery sweat a day. Eccrine glands do not cluster near hair follicles; instead they reside relatively close to the surface of the skin and discharge sweat through tiny pores. This combination of naked skin and watery sweat that sits directly atop it rather than collecting in the fur allows humans to eliminate excess heat very efficiently. In fact, according to a 2007 paper in *Sports Medicine* by Daniel E. Lieberman of Harvard University and Dennis M. Bramble of the University of Utah, our cooling system is so superior that in a marathon on a hot day, a human could outcompete a horse.

Showing Some Skin

Because humans are the only primates that lack coats and have an abundance of eccrine glands, something must have happened since our hominid lineage diverged from the line leading to our closest living relative, the chimpanzee, that favored the emergence of naked, sweaty skin.

[ALTERNATIVE IDEAS]

Why the Aquatic Ape Theory Doesn't Hold Water

Among the many theories that attempt to explain the evolution of naked skin in humans, the aquatic ape theory (AAT)—which posits that humans went through an aquatic phase in their evolution—has attracted the most popular attention and support. First enunciated by English zoologist Sir Alister Hardy in a popular scientific article in 1960, the AAT later found a champion in writer Elaine Morgan, who continues to promote the theory in her lectures and writings. The problem is, the theory is demonstrably wrong.

The AAT holds that around five million to seven million years ago tectonic upheavals in the Rift Valley of East Africa cut early human ancestors off from their preferred tropical forest environments. As a result, they had to adapt to a semiaquatic life in marshes, along coasts and in floodplains, where they lived for about a million years. Evidence of this aquatic phase, Morgan argues, comes from several anatomical features humans share with aquatic and semiaquatic mammals but not with savanna mammals. These traits include our bare skin, a reduced number of apocrine glands, and fat deposits directly under the skin.

The AAT is untenable for three major reasons. First, aquatic mammals themselves differ considerably in the degree to which they exhibit Morgan's aquatic traits. Thus, there is no simple connection between, say, the amount of hair an animal has and the environment in which it lives. Second, the fossil record shows that watery habitats were thick with hungry crocodiles and aggressive hippopotamuses. Our small, defenseless ancestors would not have stood a chance in an encounter with such creatures. Third, the AAT is overly complex. It holds that our forebears shifted from a terrestrial way of life to a semiaquatic one and then returned to living on terra firma full-time. As John H. Langdon of the University of Indianapolis has argued, a more straightforward interpretation of the fossil record is that humans always lived on land, where the driving force behind the evolution of naked skin was climate change that favored savanna grasslands over woodlands. And from a scientific perspective, the simplest explanation is usually the correct one. —***N.J.***

[WHEN NAKEDNESS EVOLVED]

ANCESTORS ON THE MOVE

Although the fossil record does not preserve any direct evidence of ancient human skin, scientists can estimate when nakedness evolved based on other fossil clues. Protohumans such as the australopithecines (*left*) probably led relatively sedentary lives, as today's apes do, because they lived in or near wooded environments rich in plant foods and freshwater. But as woodlands shrank and grasslands expanded, later ancestors, such as *Homo ergaster* (*right*), had to travel ever farther in search of sustenance—including meat. This species, which arose by 1.6 million years ago, was probably the first to possess naked skin and eccrine sweat, which would have offset the body heat generated by such elevated activity levels.

► ***Australopithecus afarensis*, represented here by the 3.2-million-year-old Lucy fossil, was apelike in having short legs that were not well suited to traveling long distances.**

VICTOR DEAK (*illustrations*); DENIS FINNIN AND JACKIE BECKETT *American Museum of Natural History* (*Lucy and Turkana Boy*)

Perhaps not surprisingly, the transformation seems to have begun with climate change.

By using fossils of animals and plants to reconstruct ancient ecological conditions, scientists have determined that starting around three million years ago the earth entered into a phase of global cooling that had a drying effect in East and Central Africa, where human ancestors lived. With this decline in regular rainfall, the wooded environments favored by early hominids gave way to open savanna grasslands, and the foods that our ancestors the australopithecines subsisted on—fruits, leaves, tubers and seeds—became scarcer, more patchily distributed and subject to seasonal availability, as did permanent sources of freshwater. In response to this dwindling of resources, our forebears would have had to abandon their relatively leisurely foraging habits for a much more consistently active way of life just to stay hydrated and obtain enough calories, traveling ever longer distances in search of water and edible plant foods.

It is around this time that hominids also began incorporating meat into their diet, as revealed by the appearance of stone tools and butchered animal bones in the archaeological record around 2.6 million years ago. Animal foods are considerably richer in calories than are plant foods, but they are rarer on the landscape. Carnivorous animals therefore need to range farther and wider than their herbivorous counterparts to procure a sufficient amount of food. Prey animals are also moving targets, save for the occasional carcass, which means predators must expend that much more energy to obtain their meal. In the case of human hunters and scavengers, natural selection morphed the apelike proportions of the australopithecines, who still spent some time in the trees, into a long-legged body built for sustained striding and running. (This modern form also no doubt helped our ancestors avoid becoming dinner themselves when out in the open.)

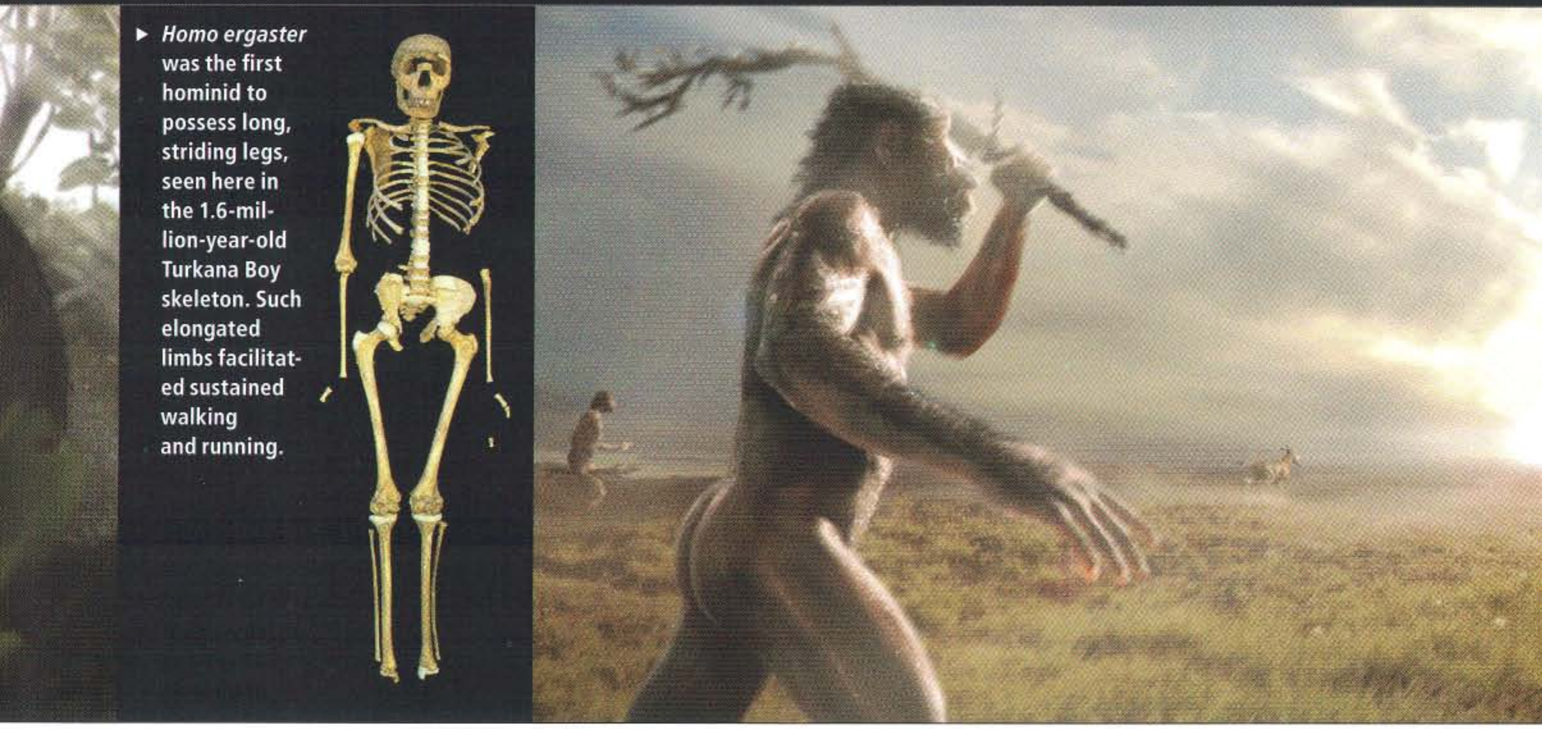
But these elevated activity levels came at a price: a greatly increased risk of overheating. Beginning in the 1980s, Peter Wheeler of Liverpool John Moores University in England published a series of papers in which he simulated how hot ancestral humans would have become out on the savanna. Wheeler's work, together with research my colleagues and I published in 1994, shows that the increase in walking and running, during which muscle activity builds up heat internally, would have required that hominids both enhance their eccrine sweating ability and lose their body hair to avoid overheating.

When did this metamorphosis occur? Although the human fossil record does not preserve skin, researchers do have a rough idea of when our forebears began engaging in modern patterns of movement. Studies conducted inde-

BEATING THE HEAT

Naked skin is not the only adaptation humans evolved to maintain a healthy body temperature in the sweltering tropics where our ancestors lived. They also developed longer limbs, increasing their surface-to-volume ratio, which in turn facilitated the loss of excess heat. That trend seems to be continuing even today. The best evidence of this sustained adaptation comes from populations in East Africa, such as the Dinka of southern Sudan. It is surely no coincidence that these people, who live in one of the hottest places on earth, also have extremely long limbs.

Why do modern humans exhibit such a wide range of limb proportions? As our forebears migrated out of tropical Africa into cooler parts of the world, the selection pressures changed, allowing for a variety of body shapes to evolve.



▸ *Homo ergaster* was the first hominid to possess long, striding legs, seen here in the 1.6-million-year-old Turkana Boy skeleton. Such elongated limbs facilitated sustained walking and running.

pendently by Lieberman and Christopher Ruff of Johns Hopkins University have shown that by about 1.6 million years ago an early member of our genus called *Homo ergaster* had evolved essentially modern body proportions, which would have permitted prolonged walking and running. Moreover, details of the joint surfaces of the ankle, knee and hip make clear that these hominids actually exerted themselves in this way. Thus, according to the fossil evidence, the transition to naked skin and an eccrine-based sweating system must have been well under way by 1.6 million years ago to offset the greater heat loads that accompanied our predecessors' newly strenuous way of life.

Another clue to when hominids evolved naked skin has come from investigations into the genetics of skin color. In an ingenious study published in 2004, Alan R. Rogers of the University of Utah and his colleagues examined sequences of the human *MC1R* gene, which is among the genes responsible for producing skin pigmentation. The team showed that a specific gene variant always found in Africans with dark pigmentation originated as many as 1.2 million years ago. Early human ancestors are believed to have had pinkish skin covered with black fur, much as chimpanzees do, so the evolution of permanently dark skin was presumably a requisite evolutionary follow-up to the loss of our sun-shielding body hair. Rogers's estimate thus provides a minimum age for the dawn of nakedness.

Going furless was not merely a means to an end; it had profound consequences for subsequent phases of human evolution.

Skin Deep

Less certain than why and when we became naked is how hominids evolved bare flesh. The genetic evidence for the evolution of nakedness has been difficult to locate because many genes contribute to the appearance and function of our skin. Nevertheless, hints have emerged from large-scale comparisons of the sequences of DNA "code letters," or nucleotides, in the entire genomes of different organisms. Comparison of the human and chimp genomes reveals that one of the most significant differences between chimp DNA and our own lies in the genes that code for proteins that control properties of the skin. The human versions of some of those genes encode proteins that help to make our skin particularly waterproof and scuff-resistant—critical properties, given the absence of protective fur. This finding implies that the advent of those gene variants contributed to the origin of nakedness by mitigating its consequences.

The outstanding barrier capabilities of our skin arise from the structure and makeup of its outermost layer, the stratum corneum (SC) of the epidermis. The SC has what has been described as a bricks-and-mortar composition. In this arrangement, multiple layers of flattened

SOCIAL SIGNALING is an important function of fur—from raised hackles indicating aggression to coat patterns that help members of the same species to recognize one another. We humans compensate for our lack of fur by decorating our bodies with tattoos, jewelry and other adornments. We also have complex facial expressions, as well as the ability to convey our emotions through language.

dead cells called corneocytes, which contain the protein keratin and other substances, are the bricks; ultrathin layers of lipids surrounding each of the corneocytes make up the mortar.

Most of the genes that direct the development of the SC are ancient, and their sequences are highly conserved among vertebrates. That the genes undergirding the human SC are so distinctive signifies, therefore, that the advent of those genes was important to survival. These genes encode the production of a unique combination of proteins that occur only in the epidermis, including novel types of keratin and involucrin. A number of laboratories are currently attempting to unravel the precise mechanisms responsible for regulating the manufacture of these proteins.

Other researchers are looking at the evolution of keratins in body hair, with the aim of determining the mechanisms responsible for the sparseness and fineness of body hair on the surface of human skin. To that end, Roland Moll of Philipps University in Marburg, Germany, and his colleagues have shown that the keratins present in human body hair are extremely fragile, which is why these hairs break so easily compared with those of other animals. This finding, detailed in a paper Moll published in 2008, suggests that human hair keratins were not as important to survival as the hair keratins of other primates were over the course of evolution and thus became weak.

Another question geneticists are eager to answer is how human skin came to contain such an abundance of eccrine glands. Almost certainly this accumulation occurred through changes in the genes that determine the fate of epidermal stem cells, which are unspecialized, in the embryo. Early in development, groups of epidermal stem cells in specific locations interact with cells of the underlying dermis, and genetically driven chemical signals within these niches direct the differentiation of the stem cells into hair follicles, eccrine glands, apocrine glands, sebaceous glands or plain epidermis. Many research groups are now investigating how epidermal stem cell niches are established and maintained, and this work should clarify what directs the fate of embryonic epidermal cells and how more of these cells become eccrine sweat glands in humans.

OF LICE AND MEN

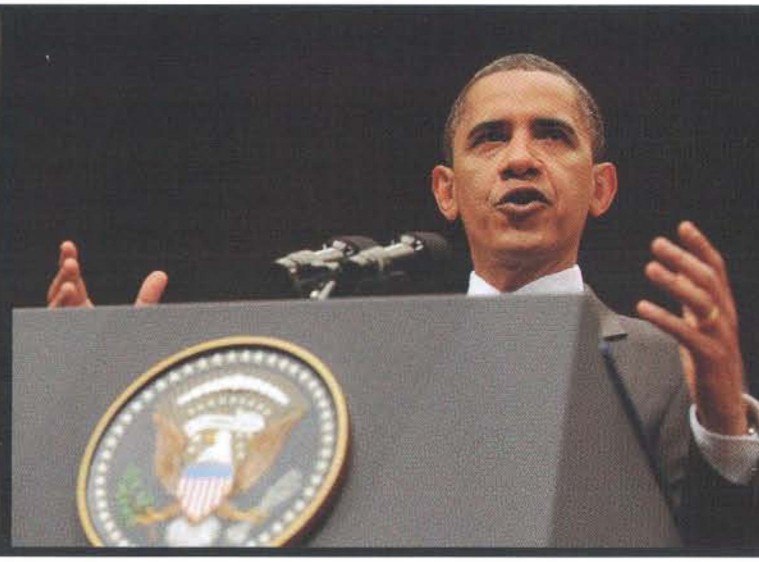
In recent years researchers have looked to lice for clues to why humans lost their body hair. In 2003 Mark Pagel of the University of Reading in England and Walter Bodmer of John Radcliffe Hospital in Oxford proposed that humans shed their fur to rid their bodies of disease-spreading lice and other fur-dwelling parasites and to advertise the health of their skin. Other investigators have studied head and body lice for insight into how long after becoming bare-skinned our ancestors began to cover up with clothing.

Although body lice feed on blood, they live on clothing. Thus, the origin of body lice provides a minimum estimate for the dawn of hominid garb. By comparing gene sequences of organisms, investigators can learn roughly when the species arose. Such analyses in lice indicate that whereas head lice have plagued humans from the start, body lice evolved much later. The timing of their appearance hints that humans went naked for more than a million years before getting dressed.

Not Entirely Nude

However it was that we became naked apes, evolution did leave a few body parts covered. Any explanation of why humans lost their fur therefore must also account for why we retain it in some places. Hair in the armpits and groin probably serves both to propagate pheromones (chemicals that serve to elicit a behavioral response from other individuals) and to help keep these areas lubricated during locomotion. As for hair on the head, it was most likely retained to help shield against excess heat on the top of the head. That notion may sound paradoxical, but having dense hair on the head creates a barrier layer of air between the sweating scalp and the hot surface of the hair. Thus, on a hot, sunny day the hair absorbs the heat while the barrier layer of air remains cooler, allowing sweat on the scalp to evaporate into that layer of air. Tightly curled hair provides the optimum head covering in this regard, because it increases the thickness of the space between the surface of the hair and the scalp, allowing air to blow through. Much remains to be discovered about the evolution of

HEINRICH VAN DEN BERG *Getty Images* (cheetah); HENRY HORNSTEIN *Getty Images* (tattoos)



human head hair, but it is possible that tightly curled hair was the original condition in modern humans and that other hair types evolved as humans dispersed out of tropical Africa.

With regard to our body hair, the question is why it is so variable. There are many populations whose members have hardly any body hair at all and some populations of hirsute folks. Those with the least body hair tend to live in the tropics, whereas those with the most tend to live outside the tropics. Yet the hair on these nontropical people provides no warmth to speak of. These differences in hairiness clearly stem to some extent from testosterone, because males in all populations have more body hair than females do. A number of theories aimed at explaining this imbalance attribute it to sexual selection. For example, one posits that females prefer males with fuller beards and thicker body hair because these traits occur in tandem with virility and strength. Another proposes that males have evolved a preference for females with more juvenile features. These are interesting hypotheses, but no one has actually tested them in a modern human population; thus, we do not know, for instance, whether hairy men are in fact more vigorous or fecund than their sleeker counterparts. In the absence of any empirical evidence, it is still anybody's guess why human body hair varies the way it does.

Naked Ambitions

Going furless was not merely a means to an end; it had profound consequences for subsequent phases of human evolution. The loss of most of our body hair and the gain of the ability to dissipate excess body heat through eccrine sweating helped to make possible the dramatic enlargement of our most temperature-sensitive organ, the brain. Whereas the australopithecines had a brain that was, on average, 400 cubic centimeters—roughly the size of a chimp's brain—*H. ergaster* had a brain twice that large. And within a million years the human brain swelled another 400 cubic centimeters, reaching its modern size. No doubt other factors influenced the expansion of our gray matter—the adoption of a sufficiently caloric diet to fuel this energetically demanding tissue, for example. But shedding our body hair was surely a critical step in becoming brainy.

Our hairlessness also had social repercussions. Although we can technically raise and lower our hackles when the small muscles at the base of our hair follicles contract and relax, our body hairs are so thin and wispy that we do not put on much of a show compared with the displays of our cats and dogs or of our chimpanzee cousins. Neither do we have the built-in advertising—or camouflage—offered by zebra stripes, leopard spots, and the like. Indeed, one might even speculate that universal human traits such as social blushing and complex facial expressions evolved to compensate for our lost ability to communicate through our fur. Likewise, body paint, cosmetics, tattoos and other types of skin decoration are found in various combinations in all cultures, because they convey group membership, status and other vital social information formerly encoded by fur. We also employ body postures and gestures to broadcast our emotional states and intentions. And we use language to speak our mind in detail. Viewed this way, naked skin did not just cool us down—it made us human. ■

MARK WILSON *Getty Images* (woman); GETTY IMAGES (Obama)

➡ MORE TO EXPLORE

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Emerging technologies could make the internal-combustion engine substantially more fuel-efficient, even as green vehicles make inroads

BETTER MILEAGE NOW

BY BEN KNIGHT

KEY CONCEPTS

- Hardware and software changes to the internal-combustion engine in cars can make it much more fuel-efficient.
- New rules due soon from the Environmental Protection Agency governing greenhouse gas emissions and from the Department of Transportation on fuel economy will force the efficiency of cars, SUVs and pickups to rise 4.4 percent a year from 2012 through 2016 and probably more in later years.
- Technologies such as direct gasoline injection, variable valve timing and cylinder deactivation can reduce the major sources of energy loss in engines: waste heat and engine friction.

—The Editors

Demand for automobiles is rising worldwide. So is concern about greenhouse gas emissions. In response, scientists and engineers are working diligently to perfect new power plants for future vehicles, including battery and hydrogen fuel-cell electric cars. Although these and other alternatives show great promise for the long term, perhaps the single greatest way to reduce fossil-fuel consumption in the near term is to further improve today's dominant transportation power plant: the gasoline internal-combustion (IC) engine.

Fortunately, efficiency can be raised in a number of ways, notably, better control over the air-fuel mixture entering the combustion chamber, over the way gasoline is ignited there, and over the mechanical systems that harness that energy. These can improve traditional automobiles as well as gasoline-electric hybrid models.

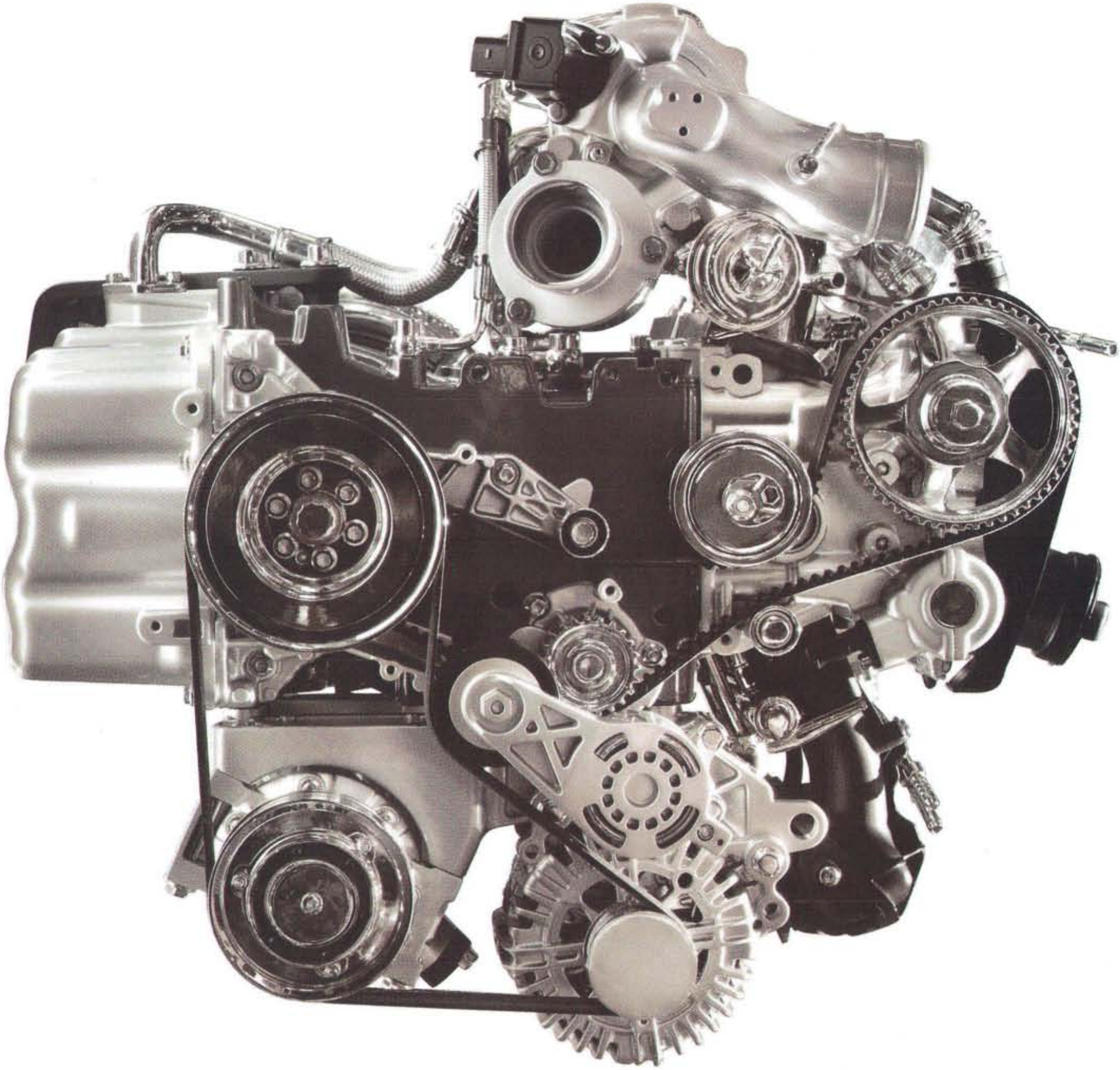
Rapidly rising fuel prices in the latter half of 2008 began steering many consumers toward vehicles offering the best fuel efficiency, but recent price declines have hurt demand for them. Strict new fuel economy and greenhouse gas emissions regulations, about to go into force, should reverse this trend, however, and drive even more significant advancements to the technology that will be under the hood of your next new car.

The modern IC engine powers all but a handful of the world's automobiles, trucks, motorcycles and motorboats. Its greatest advantage is its use of a fuel—gasoline—that is still relatively abundant, inexpensive and energy-dense. Its greatest drawback is its mediocre efficiency. The most efficient gasoline spark-ignition engines in mass-produced automobiles today convert only 20 to 25 percent of the fuel's chemical energy into work. A modern diesel or gasoline-electric hybrid power train can reach 25 to 35 percent, but at substantially higher cost. In contrast, hydrogen fuel-cell electric cars—such as Honda's FCX Clarity, now in limited production—convert about 60 percent of the energy in gaseous hydrogen into motive power.

Despite the IC engine's reputation as old and outmoded technology, however, it continues to improve. A recent Environmental Protection Agency study showed that the fuel efficiency of engines in U.S. automobiles rose by roughly 1.4 percent a year from 1987 to 2006. The increases came through incremental gains in combustion (thermal) efficiency, reductions in engine and drivetrain friction, more advanced transmissions and reduced losses in accessory systems. Most of these gains, however, did not help drivers consume less gasoline. Instead they went to meet market demand for larger, more powerful and better-equipped vehicles.

New Rules Prompt Gains

Impending regulations will help ensure that future power train efficiency gains go primarily toward actual fuel economy. The EPA is finalizing stringent new greenhouse gas standards for automobiles, and the Department of Transportation is finishing tougher corporate average fuel economy (CAFE) standards. The agencies must issue a final ruling that incorporates both



sets of requirements by April 1. In directing the DOT, Congress mandated "maximum feasible" increases in the average fuel economy of the U.S. car and light truck fleet between 2011 and 2030. Based on current proposals, the first phase of the standards will raise the fuel economy of most cars, SUVs, pickups and minivans by 4.4 percent each year from 2012 through 2016, reaching about 35.5 miles per gallon for many cars. And indications are that the bar will continue to be raised aggressively through 2020 or even 2030.

The rules will also change how greenhouse gas and fuel economy targets are calculated, which will affect how automakers will respond. Instead of setting a single standard for all cars or all light trucks in an automaker's U.S. fleet, as current standards do, the new fuel economy targets will be based on a vehicle's footprint—the rectangular area defined by the vehicle's four wheels. Each manufacturer will also have a unique target based on the sales-weighted average footprint of its combined car and light truck fleets.

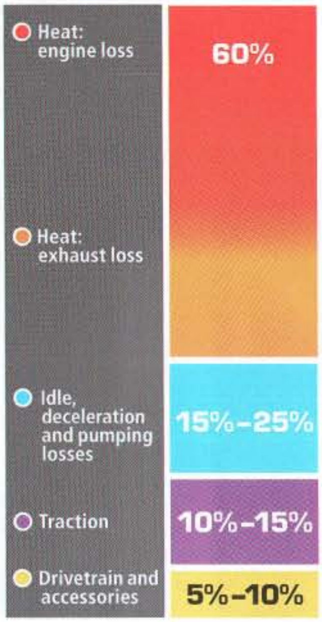
This approach means automobile companies will no longer find any advantage in building a greater number of small cars, because the resulting mix of vehicles will simply have to meet higher fuel economy and lower emissions targets for carbon dioxide. Nor will there be any real disadvantage to automakers whose fleets contain a higher percentage of larger cars and light trucks. The goal of the new standards is not to encourage or discourage the produc-

FOUR-CYLINDER ENGINE and many others like it can improve, to slow global warming.

OLEKSIY MAKSYMENKO *Alamy*

POSSIBLE ENERGY GAINS

Today's vehicles convert up to 25 percent of gasoline's chemical energy into work (*purple* and *yellow*). The rest is lost. But technologies can reduce the waste (*table*).



[THE AUTHOR]

Ben Knight is vice president of automotive engineering at Honda R&D Americas in Torrance, Calif. He oversees development of the company's low-emissions gasoline, hybrid-electric and alternative-fuel vehicles, including those powered by batteries, natural gas and fuel cells. He is also an adviser to the University of California's multicampus Transportation Sustainability program.

[FUTURE CHOICES]

Efficient Engines, One Technology at a Time

For competitive reasons, automobile manufacturers do not typically reveal their own estimates of a future technology's potential costs and benefits. But in 2008 the National Highway Traffic and Safety Administration evaluated numerous options. Note that different technologies often have overlapping benefits, which can significantly reduce the cumulative impact of using them in combination.

Technology	Fuel Economy Gain	Cost to Consumer
GASOLINE ENGINE		
Direct injection (relative to port fuel engine)	1% to 2%	\$122 to \$525
Homogeneous charge compression ignition (relative to direct injection)	10% to 12%	\$263 to \$685
Turbocharging	5% to 7.5%	\$120 (if cylinders can be reduced from 8 to 6 or 6 to 4) \$690 (4-cylinder engine)
Variable valve timing		
Two-step valve timing and lift	0.5% to 3%	\$169 to \$322
Continuous valve timing	1.5% to 4%	\$254 to \$508 (4-cylinder to 8-cylinder)
Cylinder deactivation	4.5% to 6%	\$203 to \$229 (reducing noise and vibration in 4- and 6-cylinder engines would add cost)
Camless valve operation (relative to variable valve)	2.5%	\$336 to \$673
Stop-start system	7.5%	\$563 to \$600 (including cost of 42-volt electrical system)
TRANSMISSION		
5-speed automatic (relative to 4-speed)	2.5%	\$76 to \$167
6-speed automatic (relative to 5-speed)	0.5% to 2.5%	\$10 to \$20
Continuously variable (relative to 5-speed)	3.5%	\$100 to \$139
Dual-clutch automatic (relative to automatic)	4.5% to 7.5%	\$141
TRACTIVE LOSSES		
Low rolling-resistance tires (10% reduction in resistance)	1% to 2%	\$6
Aerodynamic drag reduction	3% for cars; 2% for trucks	\$0 to \$75
Weight reduction (for each 1% lost)	0.7%	\$90 to \$150
ACCESSORIES		
Electric power steering	1.5% to 2.0%	\$118 to \$197
High-efficiency alternator and accessory electrification	1% to 2%	\$124 to \$166

NOTE: Estimates here should not be construed as an endorsement by Honda.

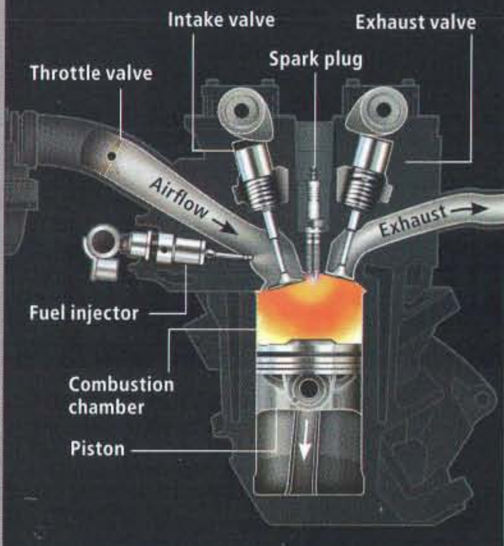
JUSTIN SCHELLER *Honda American, Inc.* (Knight); SOURCE: *NOTICE OF PROPOSED RULEMAKING ON AVERAGE FUEL ECONOMY STANDARDS, PASSENGER CARS AND LIGHT TRUCKS MODEL YEARS 2011–2015.* NHTSA, MAY 2, 2008 (table)

[ENGINE OPTIONS]

Greater Power from Every Drop

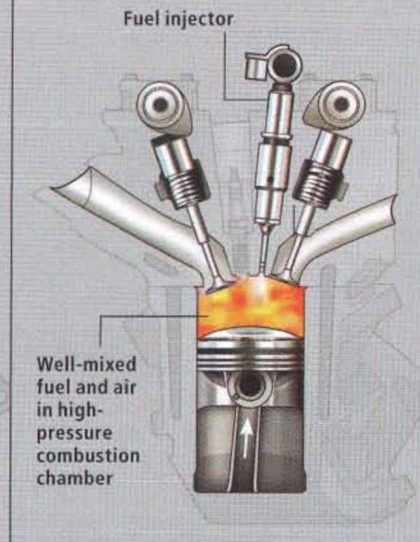
Different fuel-injection schemes burn gasoline more completely, delivering greater power to the piston while generating less waste as heat.

PORT FUEL INJECTION (common today): **When the intake valve opens, an injector sprays fuel into the air stream. The mixture enters the combustion chamber, is compressed by the rising piston, then a spark ignites it, driving the piston down. The exhaust valve opens to expel by-products. For greater power, the throttle and injector supply more air and gasoline.**



DIRECT INJECTION (available on some models): An injector sends gasoline at high pressure directly into the chamber. It vaporizes and burns more completely than in port injection, raising fuel economy, but advanced controls are needed. (Diesel engines are "direct" as well, but greater piston compression ignites fuel, without a spark.)

HOMOGENEOUS CHARGE COMPRESSION IGNITION (future): As fuel and air are injected, a rising piston compresses and ignites them, without a spark. Ignition occurs in many places at once, so less energy is lost as heat, raising efficiency. In-cylinder sensors and advanced controls are needed. A spark plug may fire when high power output is required.

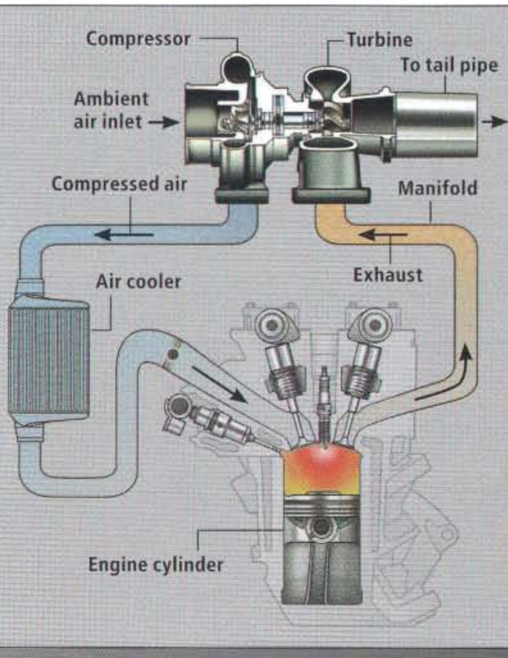


[EXHAUST OPTIONS]

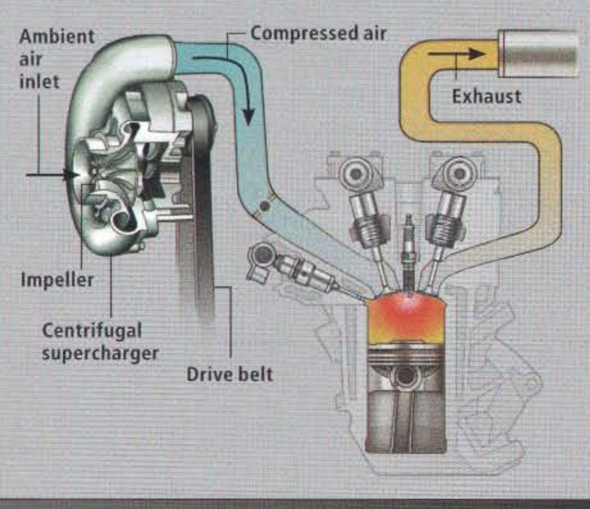
More Air Means More Propulsion

Special chargers can pressurize air fed to cylinders, boosting engine output.

TURBOCHARGER (available on some models): Exhaust normally exits through the manifold. But if a turbocharger loop (*top left*) is added, the gas stream turns a turbine, which spins a compressor. The compressor sends pressurized air to the cylinders, so more fuel can be burned and more power created, allowing the engine to be smaller, reducing friction. Controls must compensate for a lag that occurs while the turbine gets up to speed.



SUPERCHARGER (available on a few models): To raise the pressure of air entering the chamber, a supercharger is spun by a belt connected to the engine's crankshaft. In the centrifugal design, an impeller draws air in and pressurizes it. Superchargers may be less efficient than turbochargers but provide power boost without any lag.



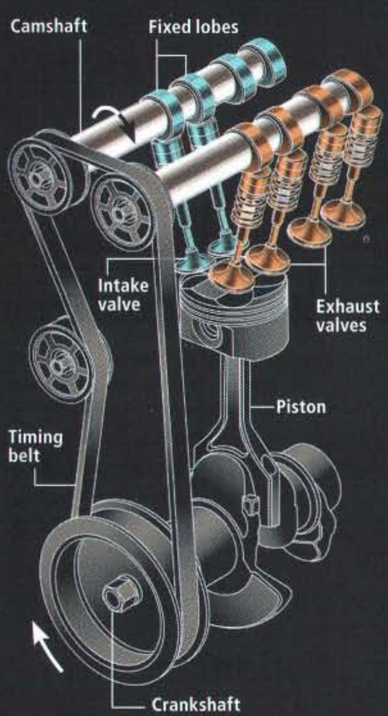
JIM HATCH

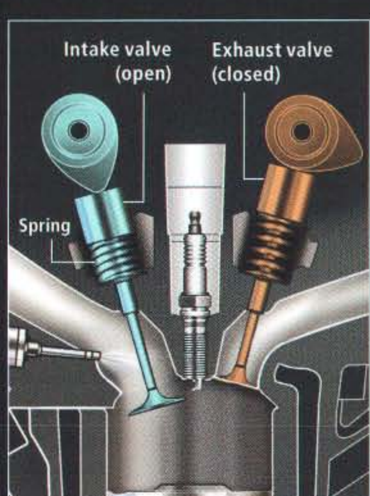
[VALVE TRAIN OPTIONS]

Customized Timing Spares Fuel

Air and exhaust valves must open and close dozens of times a second, for 100,000 miles or more. Varying, in real time, when each one rises and falls, and how much, can maximize fuel efficiency across the engine's full operating range.

CONVENTIONAL: A timing belt from the crankshaft spins the camshafts, which open and close cylinder valves (*inset below*) in a fixed sequence. But varying the valve timing could reduce losses. Also, less lift at low loads would save fuel, whereas greater lift at high loads would provide more power. Shown here: dual overhead cam engine.

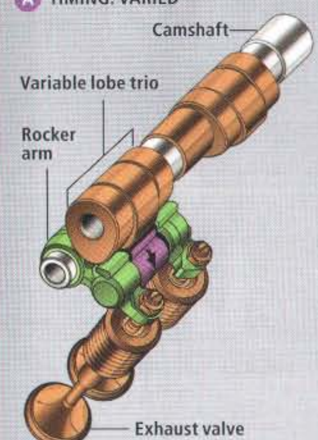




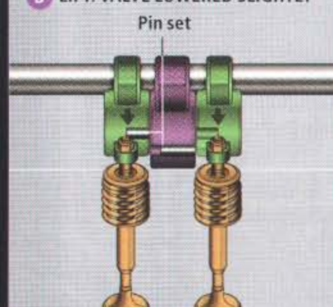
VARIABLE VALVE TIMING AND LIFT

(available on a few models): To vary timing, the position of each lobe trio is hydraulically changed to alter when it pushes a valve's rocker arm (*a*). For lift, when a pin set is disengaged (*b*), a lobe's outer rings (*green*) open the valve a shallow amount. But when hydraulics engage the pins (*c*), the larger center lobe opens the valve farther.

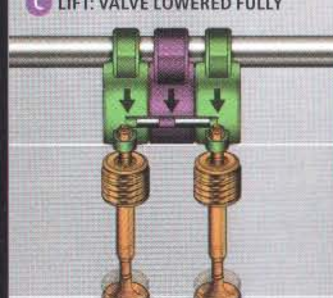
A TIMING: VARIED



B LIFT: VALVE LOWERED SLIGHTLY

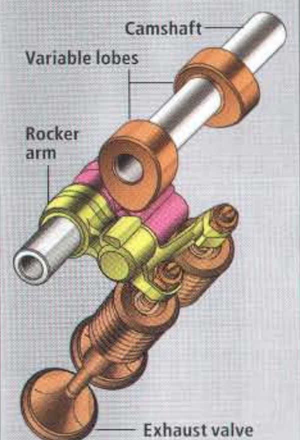


C LIFT: VALVE LOWERED FULLY

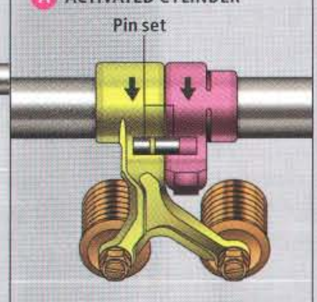


CYLINDER DEACTIVATION

(available on a few models): Shutting off cylinders when not needed (such as cruising at a steady speed) saves fuel. When a pin set links two halves of the rocker arm, they operate the valves (*a*). But when hydraulics split the pins (*b*), half the cam continues to spin (*pink*), but the valves are not activated.



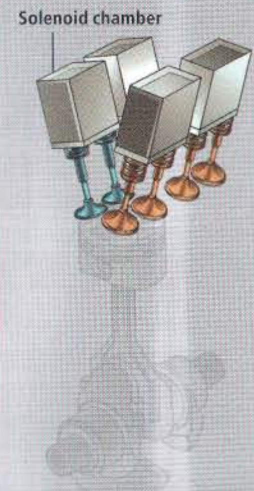
A ACTIVATED CYLINDER



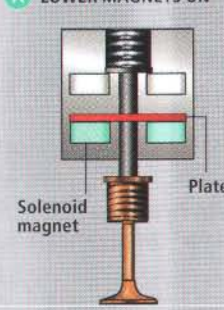
B DEACTIVATED CYLINDER

CAMLESS ENGINE

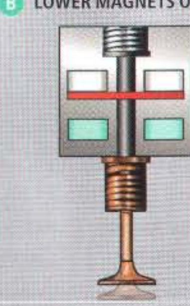
(future): Eliminating belts, pulleys and rotating shafts reduces friction greatly. In a camless design, electromagnetic solenoids switch on (*a*) and off (*b*) rapidly, moving a plate that moves the valve. Each valve's timing and lift is infinitely variable. Reliability and low cost have yet to be achieved.



A LOWER MAGNETS ON



B LOWER MAGNETS OFF



JIM HATCH

tion or purchase of any class of vehicle but to make every class as fuel-efficient as possible, within the bounds of what regulators deem to be both economically practical and technically feasible.

Cutting Losses in Many Ways

The new regulations present automakers with a daunting challenge: how to best invest limited engineering resources to dramatically raise IC engine efficiency in a very short time, while continuing to meet consumers' demands for performance, safety, utility and comfort.

The most compelling options would reduce the major sources of energy loss. About 60 percent of the energy in combusted gasoline is lost to heat—roughly half of that through the engine and half through the exhaust. Another 15 to 25 percent is lost to engine friction and to fuel consumed when the engine is idling or the car is decelerating—when no usable work is being done. Engine friction includes so-called pumping losses created by the process of pulling air past a partially closed throttle valve into the cylinders, to burn with fuel.

The remaining energy is engine output. Half to two thirds of it (10 to 15 percent of the gasoline's total energy) is used to overcome the vehicle's tractive hurdles: inertia (reflecting the car's weight), aerodynamic drag and rolling resistance (friction between tires and the road). The balance (5 to 10 percent of the total) is consumed by the drivetrain (transmission and drive shafts to the axles) and by accessories such as power steering, air conditioning and the alternator that creates electricity for such equipment.

Efficiency can be improved in every one of these areas, and even minor advances can yield substantial benefits. For example, a 1 percent reduction in tractive losses translates into a 4 to 5 percent improvement in fuel economy. The challenge is to implement a set of technologies that offers the highest efficiency gains at the lowest cost. Because each automaker has a unique fleet and particular technological strengths and weaknesses, each company will likely choose a different mix of enhancements.

An exhaustive list of advancements is beyond the scope of this article. For example, reducing engine friction involves materials, geometry of the moving parts, lubricants and parts design; dozens of minor changes can be combined to improve efficiency by a few percent. Nevertheless, most automotive engineers would probably agree on a short list of approaches that are very promising and widely applicable within the next decade. These items appear in the table on page 52, and some are illustrated in this article.

Superengine

As we look even further ahead, additional gains in IC engine efficiency will rely heavily on system optimization. Combinations of hardware and software are virtually limitless. One kind of future "superengine" would employ several of the advances depicted here: direct injection of gasoline, with continuously variable timing of camless piston valves, combined with a hybrid-electric motor and a turbocharger (which boosts power by harnessing waste gases streaming through the exhaust system).

In this hypothetical system, the batteries alone would power driving at low speeds and loads. When the engine comes on, to maximize efficiency it would switch among various modes, or operating cycles, that are common to combustion engines, such as the Atkinson cycle and the Otto cycle (a conventional engine can operate only in one mode). The hybrid motor and turbocharger would provide instant power during acceleration. And exhaust gas—a free source of energy—would be tapped to generate electricity that r;echarges the batteries.

For a car optimized in this way, the engine could be one half to one third of the size of current engines, reducing friction losses and cutting weight to boot. Such a system would offer major efficiency benefits, but it would also be extremely complex and costly. One important task would be implementing software that could determine the best operating strategy for every speed and load condition and control the engine as it switched between modes.

In the long run, and in the face of an inevitable downturn in oil supplies, the world needs as many practical alternatives to gasoline as science and engineering can muster. But the allure of advanced vehicles should not stall the progress industry can and should make to improve IC engine efficiency right now. No single technology or energy source can satisfy the world's growing transportation energy demands. But substantial gains in IC engine efficiency, along with expanded use of hybrid technology, will help smooth the transition from petroleum to more renewable fuel options. In this context, the gasoline IC engine can be viewed not as the enemy to progress but as a weapon in the battle to reduce greenhouse gas emissions and bring about a cleaner and more sustainable future. ■

STOP. START.

Hybrid cars save fuel in part by turning off the engine when the vehicle is stopped, coasting or braking; batteries alone provide power. A purely gasoline engine could do the same. It would need a powerful starter that instantly turns the engine back on under any condition, which would likely require a 42-volt electrical system and battery, more robust than the 12-volt systems in vehicles today. A start-stop feature could raise fuel economy by up to 7.5 percent **[*see table on page 38*].**

➡ MORE TO EXPLORE

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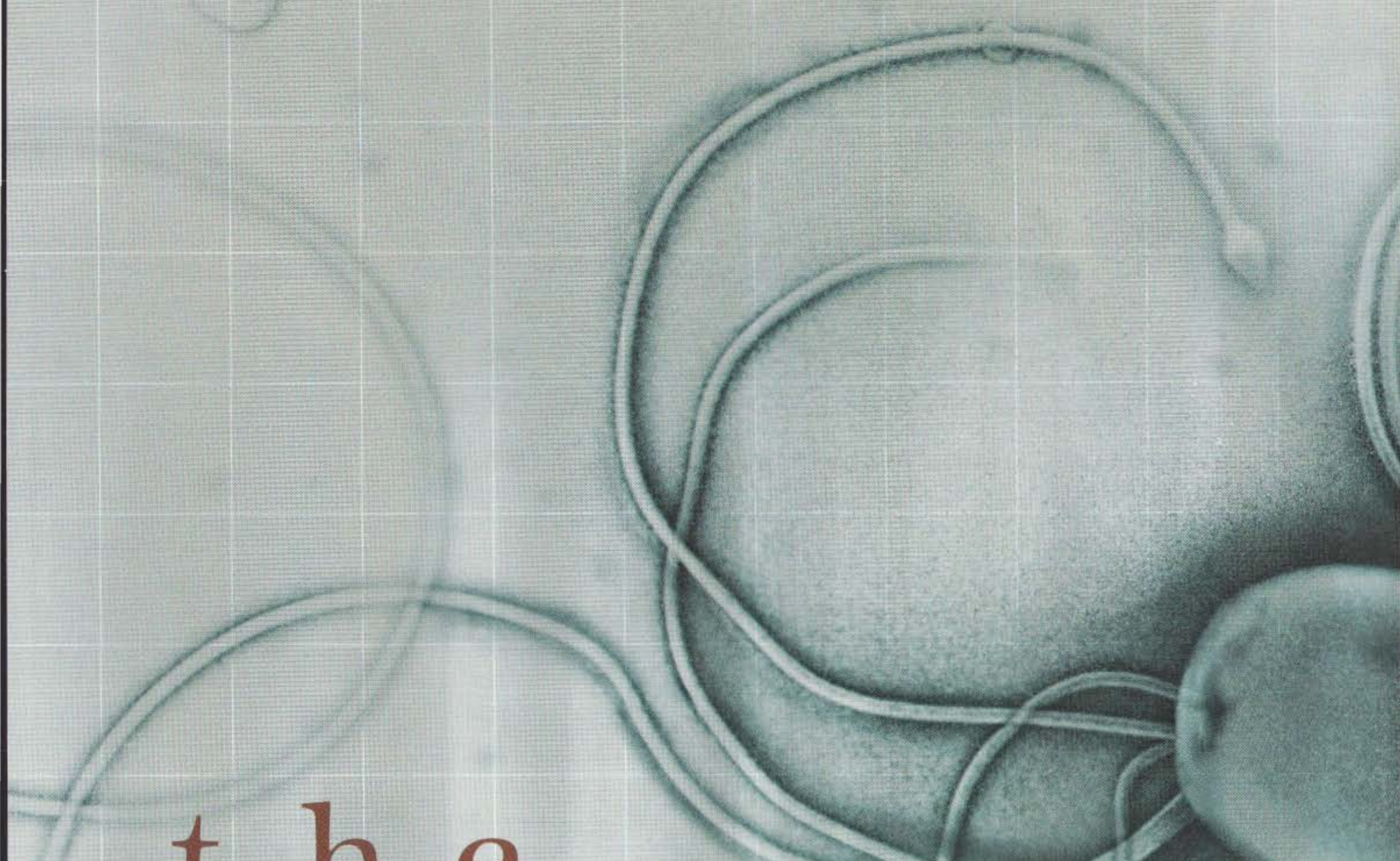


the art of bacterial warfare

New research reveals how bacteria hijack our body's cells and outwit our immune system—and how we can use their own weapons against them

By B. Brett Finlay

Most bacteria are well-behaved companions. Indeed, if you are ever feeling lonely, remember that the trillions of microbes living in and on the average human body outnumber the human cells by a ratio of 10 to one. Of all the tens of thousands of known bacterial species, only about 100 are renegades that break the rules of peaceful coexistence and make us sick.

Collectively, those pathogens can cause a lot of trouble. Infectious diseases are the second leading cause of death worldwide, and bacteria are well represented among the killers. Tuberculosis alone takes nearly two million lives every year, and *Yersinia pestis,* infamous for causing bubonic plague, killed approximately one third of Europe's population in the 14th century. Investigators have made considerable progress over the past 100 years in taming some species with antibiotics, but the harmful bacteria have also found ways to resist many of those drugs. It is an arms race that humans have been losing of late, in part because we have not understood our enemy very well.

Historically, microbiologists sought to learn how bacteria cause disease by growing them in a nourishing broth, then isolating molecules from the bugs' exterior or extracting their secretions from the medium, and examining the effects of those substances on human cells and animals. Such studies characterized assorted bacterial toxins, but most investigations of the mechanisms of disease virtually ignored the interplay between bacterial pathogens and their hosts. Over the past 20 years, however, a growing body of research has revealed that disease-causing bacteria often

KEY CONCEPTS

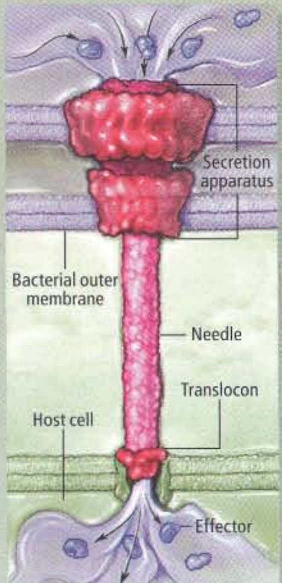
- Bacterial pathogens multiply and make toxins inside human hosts, but how the microbes elude our defenses and deliver their poisons have been poorly understood.
- Studying host-pathogen interactions reveals sophisticated bacterial strategies for co-opting and manipulating host cells to serve a bacterium's needs.
- A new understanding of bacterial tools and tactics is leading to novel approaches for battling the microbes.

—The Editors

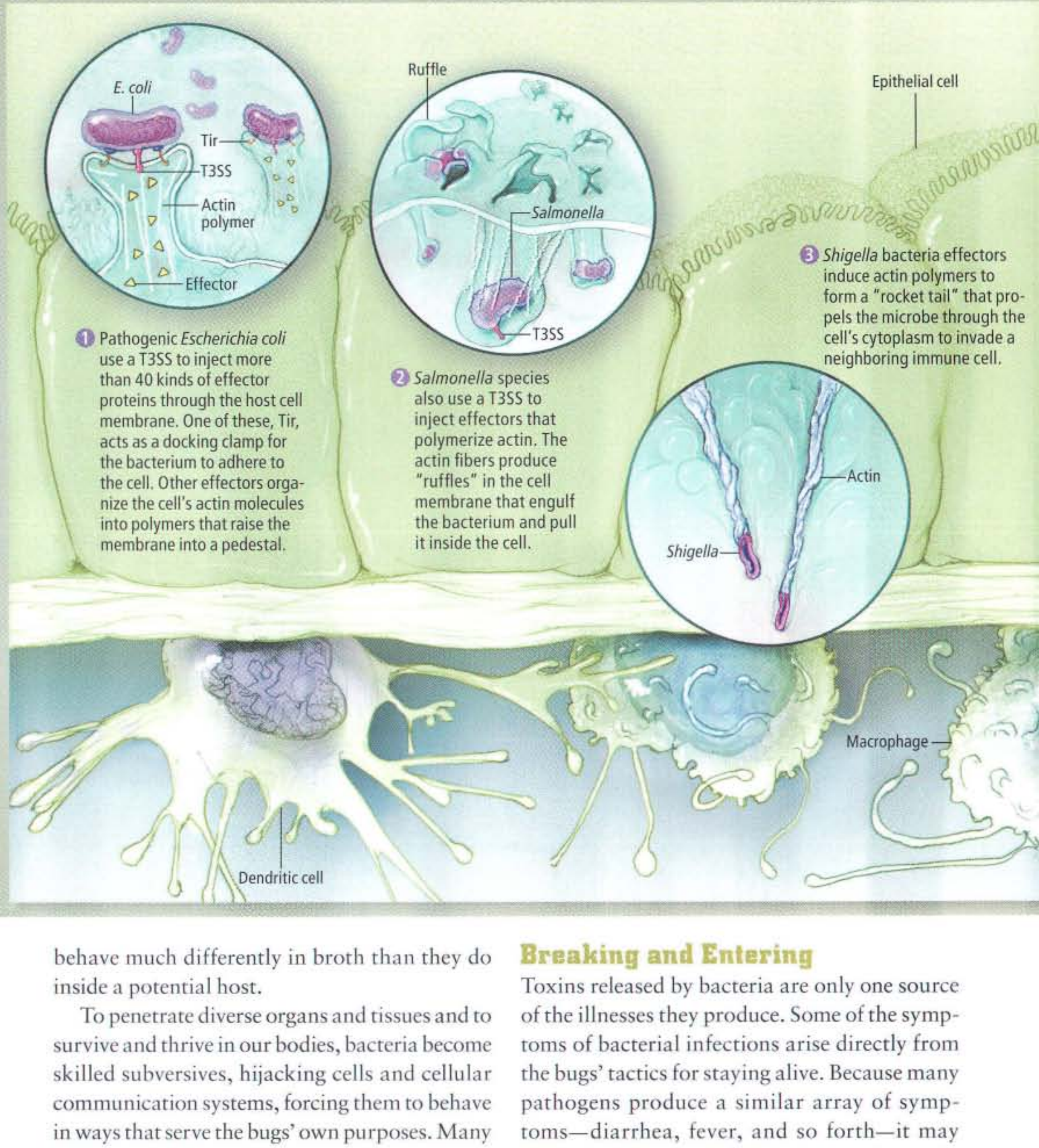
[TACTICS AND TOOLS]

How Bacteria Hijack Host Cells

Disease-causing bacteria actively promote their own survival by co-opting host cells' machinery and communications to do the microbes' bidding and by altering the environment inside and outside cells to suit their needs. In the examples below, microbes invading the intestine wield specialized tools (*inset at far left*) to manipulate a variety of cell types, including epithelial cells, immune cells and harmless bacteria that reside in the gut.



SECRETION SYSTEMS
Specialized devices allow bacteria to inject cell-controlling "effector" molecules directly into host cells. The type 3 secretion system (T3SS) above is typical. The main secretion apparatus in the bacterial membrane lowers the hollow needle to the host cell and delivers a translocon protein to anchor the needle; effector proteins follow.



1. Pathogenic *Escherichia coli* use a T3SS to inject more than 40 kinds of effector proteins through the host cell membrane. One of these, Tir, acts as a docking clamp for the bacterium to adhere to the cell. Other effectors organize the cell's actin molecules into polymers that raise the membrane into a pedestal.

2. *Salmonella* species also use a T3SS to inject effectors that polymerize actin. The actin fibers produce "ruffles" in the cell membrane that engulf the bacterium and pull it inside the cell.

3. *Shigella* bacteria effectors induce actin polymers to form a "rocket tail" that propels the microbe through the cell's cytoplasm to invade a neighboring immune cell.

JESSICA WEISMAN (*bacterium on preceding two pages and wire human on opposite page*)

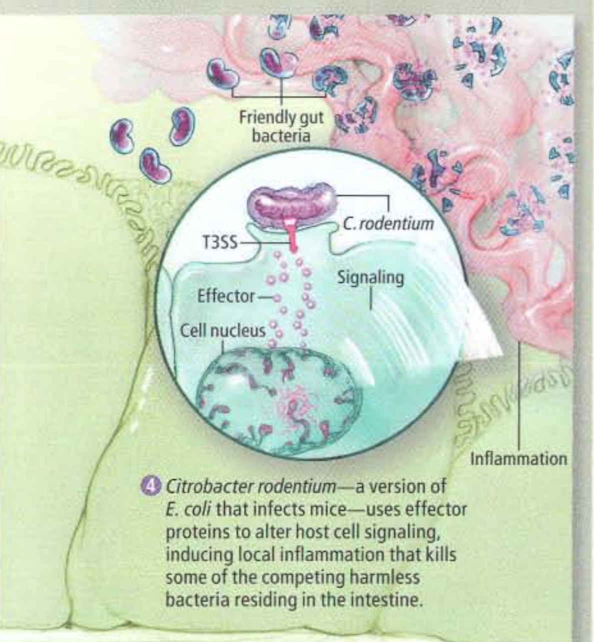
behave much differently in broth than they do inside a potential host.

To penetrate diverse organs and tissues and to survive and thrive in our bodies, bacteria become skilled subversives, hijacking cells and cellular communication systems, forcing them to behave in ways that serve the bugs' own purposes. Many microbes take control by wielding specialized tools to inject proteins that reprogram the cellular machinery to do the bugs' bidding. A few are also known to employ tactics that rid the body of benign or beneficial bacteria, to better commandeer the environment for themselves. As investigators have identified the aggressive strategies and ingenious weapons used by pathogenic bacteria to invade and outwit their hosts, we have wasted no time in trying to devise therapies that turn the microbes' own weapons against them.

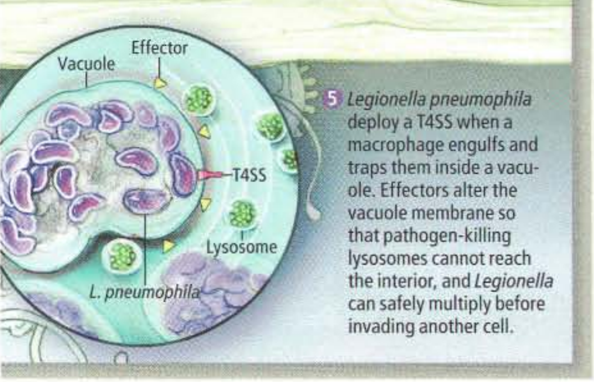
Breaking and Entering

Toxins released by bacteria are only one source of the illnesses they produce. Some of the symptoms of bacterial infections arise directly from the bugs' tactics for staying alive. Because many pathogens produce a similar array of symptoms—diarrhea, fever, and so forth—it may seem logical to think that they cause disease in similar ways, too. Although many pathogens do act on some of the same fundamental elements of cellular machinery, such as certain proteins that make up the cell's internal skeleton, the microbes use surprisingly diverse and complex methods to attack.

The first step in any bacterial assault, for instance, is attachment to the host's cells. A disease-causing strain of *Escherichia coli*, known as enterohemorrhagic *E. coli* O157, has perhaps



4 *Citrobacter rodentium*—a version of *E. coli* that infects mice—uses effector proteins to alter host cell signaling, inducing local inflammation that kills some of the competing harmless bacteria residing in the intestine.



5 *Legionella pneumophila* deploy a T4SS when a macrophage engulfs and traps them inside a vacuole. Effectors alter the vacuole membrane so that pathogen-killing lysosomes cannot reach the interior, and *Legionella* can safely multiply before invading another cell.

ANDREW SWIFT (*bacterial hijacking illustrations*)

the most remarkable method of locking itself onto a host cell. People typically pick up this pathogen by eating tainted food; once inside the gastrointestinal tract, O157 attaches to the intestinal wall and produces a toxin that induces bloody diarrhea. At one time, scientists thought that this virulent form of *E. coli*, like all other adherent pathogens, latched onto a receptor molecule already present on the host's intestinal cells. More recent work has shown, though, that O157 actually makes its own receptor and delivers it into the cell through a specialized device known as a type 3 secretion system, or T3SS for short. (Secretion systems have historically been named based on the order of their discovery.)

The bacterium's T3SS injects a molecule called Tir, along with 40 or more other "effector" proteins directly into the membrane of the host cell and then locks one of its own surface molecules onto Tir. But that is only its first step in taking over the cell. Tir and some of the other injected effectors also induce the host cell's internal skeleton to behave abnormally. A key cytoskeletal building block, actin, interacts with the bacterial proteins and begins forming polymers that push on the cell membrane from the inside until it forms a pedestal. The *E. coli* remains outside the cell, securely anchored to its new throne, while the effectors and toxins it has injected into the cell do their dirty work. The exact function of these striking pedestals remains unknown, but investigators have demonstrated that they are central to the bacterium's ability to cause disease.

Another potentially lethal pathogen, *Helicobacter pylori*, attaches itself to the epithelial cells lining the stomach, then begins customizing its environment to promote its own survival. *H. pylori* releases an enzyme called urease that locally counters the stomach's high acidity, which normally kills most bacteria. Not all strains cause disease, but those that do can generate gastric ulcers and even stomach cancer—making it the only bacterium known to cause cancer. The pathogenic strains produce a type 4 secretion system that injects an effector protein called CagA. The protein's exact purpose is unclear, but recent work suggests that it can induce stomach epithelial cells to display more of the receptors to which *H. pylori* attaches. The effector may also directly alter the stomach cells' internal signaling in a way that makes them elongate, scatter and ultimately die, contributing to ulcer formation.

E. coli O157 and *H. pylori* bacteria do not need to enter cells to cause disease, but *Salmonella* species, which are closely related to *E. coli* and cause diarrhea in more than a billion people worldwide every year, do penetrate cell walls. Indeed, to thrive, *Salmonella* bacteria have to pass into and through epithelial cells that line the intestine. This invasion begins when the bacteria use a T3SS variant known as *Salmonella* pathogenicity island 1 (SPI-1) to inject epithelial cells with effectors that reorganize actin polymerization in a way that produces "ruffles" in the cell membrane—similar to *E. coli*'s pedestal. The ruffle structures reach up and around a bacterium attached to the outside of the cell membrane, causing the cell to literally drag the microbe inside. Molecules injected through SPI-1 also induce the diarrhea characteristic of these infections, but the *Salmonella* bacteria do not stop there.

Macrophages and other cells belonging to

HUMAN MICROBIOTA

HUMAN BODY COMPOSITION

10 TRILLION
human cells

100 TRILLION
bacterial cells

BACTERIAL SPECIES LIVING IN THE HUMAN ...

5,000–35,000
... intestine

300–500
... mouth

120
... skin

BACTERIAL SPECIES PATHOGENIC TO HUMANS

100

PERCENTAGE OF HUMANS COLONIZED (WITH OR WITHOUT ILLNESS) BY COMMON PATHOGENS

33%
Mycobacterium tuberculosis

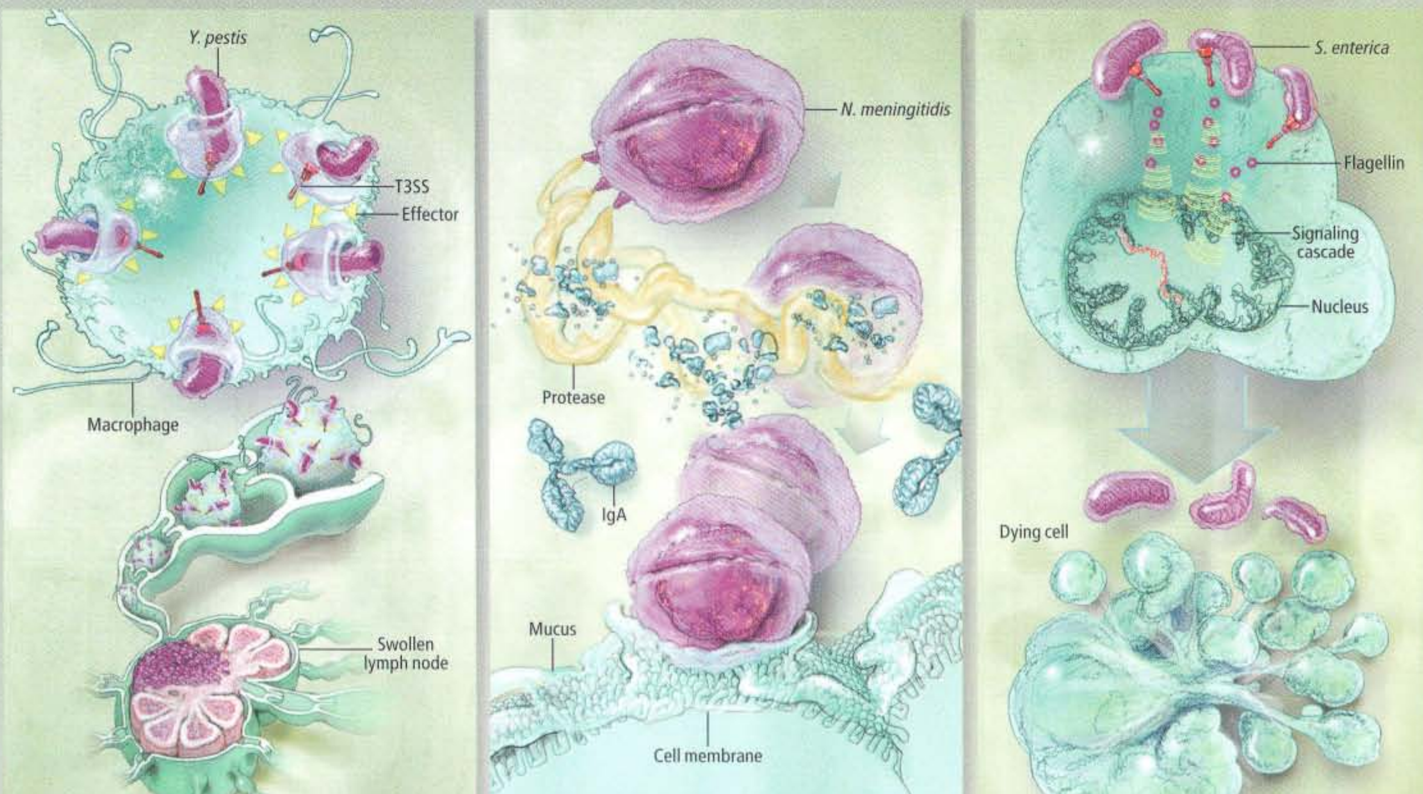
50%
Helicobacter pylori

50%
Staphylococcus aureus

[EVADING IMMUNITY]

Outwitting the Guards

Immune cells and the antibodies they manufacture are supposed to neutralize invaders, but bacterial pathogens can evade those host defenses with diverse tools and tactics, such as depicted in the examples below.



DISABLING MACHINERY
When a macrophage tries to engulf *Yersinia pestis*, the bacterium uses its T3SS to inject effectors that paralyze the immune cell's uptake machinery. *Yersinia* then ride the cell into lymph nodes, where the microbes multiply, causing the swollen nodes called bubos that are characteristic of bubonic plague.

DESTROYING ANTIBODIES
Immunoglobulin A (IgA) antibodies block bacteria from adhering to epithelial cells that line nasal passages and similar mucosal surfaces in the body. But *Neisseria meningitidis*, a cause of meningitis, can colonize such cells by first releasing a protease (enzyme) that degrades the antibodies.

TRIGGERING SELF-DESTRUCTION
Certain host cells such as macrophages train other immune cells to recognize a pathogen, but *Salmonella enterica* prevents that from happening. The bacterium uses its T3SS to inject the cell with flagellin, a protein that sets off signaling cascades that ultimately trigger a cell suicide mechanism.

what is called the innate arm of the immune system, such as neutrophils and dendritic cells, normally ingest and destroy ("phagocytose") any invaders. These phagocytes engulf bacteria and sequester them in membrane-bound vacuoles where killing molecules destroy the captives. But *Salmonella* species penetrate the intestinal lining by passing from epithelial cells to immune cells waiting on the other side. Once inside the phagocytic vacuole, the bacteria deploy a second T3SS, called SPI-2, which releases effector proteins that convert the vacuole into a safe haven where *Salmonella* can multiply. The proteins cause this switch from death chamber to sanctuary by altering the vacuole membrane so that the killing molecules cannot get in.

The SPI-2 system is critical to the success of *Salmonella typhi*, the strain that causes typhoid fever. By allowing the microbes to survive inside the phagocytic cells, which travel within the body via the bloodstream and lymphatic system, SPI-2 enables the organisms to reach and replicate in tissues far beyond the intestine, such as the liver and spleen.

An ability to live long term inside a host's cells is a trait common to many bacterial pathogens that cause serious disease, including those responsible for tuberculosis and Legionnaires' disease. Indeed, *Legionella pneumophila* is particularly intriguing in that it injects at least 80 different effectors into phagocytic cells through its T4SS. Although the function of only a handful of these proteins is known, at least some of them serve to convert the phagocytic vacuole into a safe haven.

Legionella's behavior also offers a window

ANDREW SWIFT

into the likely origin of bacterial secretion systems, which apparently evolved not to sicken humans but to protect the bugs from attack by single-celled organisms in the soil. *Legionella* normally uses its T4SS to survive when ingested by soil amoebas, which are remarkably similar in many of their mechanisms to human phagocytic cells. This association with amoebas even gave the microbe its name. At an American Legion meeting in Philadelphia in 1976, amoebas containing *Legionella* bacteria were blown through air-conditioning ducts into the hotel and delivered deep into the conventioneers' lungs. Macrophages in the humans' alveoli ingested the *Legionella,* much as an amoeba would. Thirty-four people died of the resulting respiratory illness, and Legionnaires' disease was born.

Dodging the Sentries

The ability of bacteria to set up housekeeping inside immune cells—the very cells meant to kill them—attests to the versatility of the microbes' tool kit for co-opting cellular machinery. The similarity between human immune cells and bacterial predators outside human hosts may explain the origin of other bacterial survival tactics as well. Some of the most sophisticated mechanisms that bacteria are known to deploy are devoted to evading host defenses and even enlisting immune cells to help the microbes thrive.

Y. pestis, for instance, is transmitted from rats to humans by flea bites that deliver the microbe directly into the blood. When circulating phagocytic cells attempt to engulf and kill the pathogen, *Yersinia*'s T3SS injects a set of at least four effectors that collectively paralyze the phagocytic machinery before the immune cells can swallow their prey. The circulating phagocytes, with *Yersinia* bacteria adhering to their surface, then filter into the lymph nodes, where the microbes start multiplying, causing the painful swellings, or bubos, that give bubonic plague its name.

Many pathogens have evolved secretion/injection systems able to selectively reprogram cell signaling and immune responses. *Shigella dysenteriae,* the causative agent of dysentery, exemplifies the range of tactics that a single species of bacteria can sometimes employ in the course of infection. Although *Shigella* bacteria are extremely similar genetically to harmless strains of *E. coli, Shigella* possess a T3SS that injects 25 to 30 effectors, which cause host cells to take up the microbes, much as *Salmonella* are drawn in. *Shigella* then co-opt the cytoskeletal machinery to travel through the cell and penetrate a neighboring cell, thus avoiding any encounters with immune cells and antibody molecules that might wait outside the cells.

Shigella's other immune evasion and reprogramming mechanisms are not completely understood, but several of its effectors are known to interact directly with the internal signaling systems in host cells in ways that neutralize some of the distress calls an infected cell would normally send out. Not all host cell signals are silenced, however. The microbe also counts on a certain amount of signaling to draw dendritic cells to the site of infection. It then penetrates those phagocytic cells, using them as a Trojan horse to carry them through the intestinal wall—a journey that disrupts the wall and causes the severe diarrhea characteristic of dysentery.

It is not only the innate immune system that bacteria dupe. Some have learned to avoid the "acquired" immune response, which consists of T cells and antibody-producing B cells that are trained by innate immune cells to recognize a specific pathogen by its surface features (antigens). Microbes may dodge these defenses, either by constantly changing surface proteins to evade antibodies or by secreting enzymes that degrade antibodies. *Shigella* is one of several pathogens able to block antibodies from ever being made, by preventing phagocytic cells from presenting antigens to the cells of the acquired immune system. *Salmonella* is also able to trigger an internal signaling cascade that induces phagocytic cells to commit suicide before they can interact with cells of the acquired immune system.

A Competitive Community

To thrive in a body, pathogens need to do more than manipulate cell signaling and outwit immune defenses. They also have to outcompete the body's hordes of normal, friendly bacteria—players that were virtually ignored by most microbiologists and immunologists until recently. All the surfaces of the body exposed to the environment, including the lining of the gastrointestinal tract, contain an enormous population of these "commensal" microbes. Each gram of the large intestine's contents, for example, contains approximately 60 billion bacteria—10 times the number of people on the planet.

One of the most obvious ways to eliminate competition is to cause diarrhea and thereby flush one's opponents out of the body, at least temporarily. My colleagues and I have shown that a mouse version of pathogenic *E. coli,*

Secretion systems evolved not to sicken humans but to protect the bugs from attack by single-celled organisms in the soil.

[THE AUTHOR]

B. Brett Finlay is the Peter Wall Distinguished Professor in the Michael Smith Laboratories, the biochemistry and molecular biology department, and the microbiology and immunology department at the University of British Columbia. His research centers on host-pathogen interactions at the molecular level and has led to several fundamental discoveries. Finlay has won numerous scientific awards and is a co-founder of Inimex Pharmaceuticals, as well as director of the SARS Accelerated Vaccine Initiative.

COURTESY OF B. BRETT FINLAY

Many pathogens have evolved from harmless microbes by acquiring genes that confer new properties.

known as *Citrobacter rodentium*, intentionally triggers inflammation of the intestine, an influx of innate immune cells that kills off a particular subset of the animal's normal gut microbiota. Without these rivals for resources, the pathogens multiply rapidly, and their dominance lasts until the acquired immune system becomes activated against them. The immune cells ultimately clear the pathogens, and then normal flora repopulate the gut, returning to approximately their original composition and numbers.

Similarly, a mouse version of *Salmonella* adapts its behavior to the makeup of the host's microbiota. The bacterium usually causes a systemic typhoidlike disease in mice; however, if the normal mouse microbiota are altered in advance by pretreating the mice with high doses of antibiotics, the pathogen produces a disease that is limited to the gastrointestinal tract. Competition from the resident gut microbes seemingly drives the *Salmonella* to invade the body and cause systemic illness, but when the resident flora are changed, *Salmonella* are content to remain in the gut.

Interactions among microbes, both pathogenic and benign, inside a host's body also provide opportunities for pathogens to gain and exchange weapons. Indeed, many pathogens have evolved from harmless microbes by acquiring genes that confer new properties. In this sense, the gut can be considered a great microbial genetic Internet, allowing the sharing of genes encoding "virulence factors"—the tools and tricks that enhance bacterial virulence, such as secretion systems or effector proteins.

Acquiring new pathogenicity islands can give the microbe an advantage by allowing it to colonize a new host or to become more aggressive. The deadly *E. coli* O157, for example, is thought to have appeared for the first time in the late 1970s, when a relatively benign *E. coli* acquired a pathogenicity island encoding a new T3SS and gained the gene for making Shiga toxin—properties that together produce severe diarrhea and kidney disease in O157 infections.

Building New Weapons

Discovery of injection systems and other tools that help pathogens to survive and thrive inside a host is suggesting ideas for therapy that go beyond the classic antibiotic strategy of directly damaging bacterial cells. My research group, for instance, has taken advantage of our knowledge of secretion systems to devise a novel vaccine against *E. coli* O157.

The vaccine contains pieces of the pathogen's T3SS as well as several of its effectors, so the acquired immune system can learn to immediately recognize and neutralize the proteins, preventing the bacterium from deploying them. This particular vaccine protects people from afar: it is for cows. *E. coli* O157 resides harmlessly in about half of domesticated cattle, but cow fecal matter can spread it to human food and water supplies, which is why this pathogen most often causes illness through tainted meat or produce. By eliminating O157 at its source, the vaccine—which is now used in Canadian cattle and is undergoing approval in the U.S.—can help keep O157 from ever finding its way to a human host.

Many investigators are exploring other creative strategies for disabling pathogens. Once a bacterium's virulence factors are known, one might develop therapies that render the microbe harmless by shutting off the genes that give rise to those factors. A related approach is creating molecules that block a bacterium's cell adhesion molecules—preventing it from gaining a foothold in the host. Such an antiadhesin targeted against pathogenic *E. coli* has already completed human efficacy trials, and similar drugs are in earlier stages of development.

Interfering with organisms' ability to communicate with one another is also an intriguing possibility. Bacteria such as *E. coli* gauge their location in the gut by "listening" to chemical signals from normal microbiota and host cells, and that information plays a part in their decision to attack. Another pathogen, *Pseudomonas aeruginosa*, forms colonies called biofilms in the lungs, and investigators at the University of Copenhagen recently showed that constituents of the biofilm send out signals to warn of approaching immune cells, which causes the other bacteria to secrete an immune cell–killing peptide.

One of the advantages of targeting bacterial factors that help make us sick is that those molecules are not usually essential to the microbe's ability to survive outside our bodies. In contrast to traditional antibiotics, which attempt to kill pathogens outright, newer treatments blocking communication and other virulence mechanisms would leave organisms harmless but alive, and so resistance to the treatments would probably arise more slowly, if at all.

Even more indirect methods of subverting pathogens focus on making the environment unfriendly for them. The prospect that host microbiota could be altered to compete with pathogens is being hotly pursued by many investiga-

VITAL VACCINE: **Cattle can carry *E. coli* O157:H7 without becoming sick, but the bacteria can cause lethal kidney failure in humans. Econiche, a cattle vaccine against the pathogen, is licensed in Canada and awaiting approval in the U.S. It protects people by keeping the pathogen out of the food supply.**

LANCE IVERSEN *San Francisco Chronicle/Corbis*

[THERAPIES]

Targeting Bacterial Weapons

With a better understanding of the tools bacteria use to subvert host cells and defenses, scientists are developing a variety of approaches to counter the bugs' attack. A few of the examples below are in early (phase 1 or phase 2) human testing, but most are in preclinical (laboratory) stages of development.

TARGET	SUBSTANCE (HOW IT WORKS)	TESTING STAGE
Adhesion to human cells	**Immunoglobulin** (blocks operation of bacterial adhesion proteins)	Phase 2*
	Glycodendrimers (act as decoys for bacterial adhesion proteins)	Preclinical
	Pilicides (impede manufacture of adhesion proteins)	Preclinical
Type 3 secretion systems	**Salicylidene acylhydrazides** (block assembly of secretion system)	Preclinical
Virulence genes	**Virstatin** (blocks manufacture of toxin and adhesion molecules)	Preclinical
	Inhibitory autoinducing peptides (block manufacture of communication molecules)	Preclinical
Communication	**Azithromycin** (interferes with multiple aspects of bacterial communication)	Preclinical*
Host immune cells	**IMX942** (modifies signaling and inflammation)	Phase 1 (Canada)
	Sodium butyrate (induces production of antimicrobial peptides)	Phase 2

Already FDA-approved for other uses.

tors. The principle of introducing probiotics (harmless bacteria such as *Lactobacillus*) and prebiotics (sugars to enhance growth of beneficial bacteria) to protect against disease is widely known, and many people have used substances such as yogurt to try to enhance their commensal populations. But those strategies have not yet been tested rigorously enough to determine which friendly bacteria would be most beneficial, nor has anyone identified specific microbes that would be powerful enough to combat an established infection.

Work is somewhat further along in finding ways to boost the ability of human immune cells to fight off pathogens, however. Many immune-stimulating substances are already widely used in minute amounts as additives to vaccines, without harmful side effects. And several biotechnology companies are currently in early stages of research or in early clinical trials with new substances designed to enhance or refine natural immune responses. This approach could be used to augment other therapies and possibly to prevent or even treat active infections.

Perhaps the greatest hurdle in the effort to develop new drugs for this purpose is uncoupling the beneficial aspects of inflammation—its normal role is to rally needed immune cells to battle the invader—from harmful levels of inflammation that can hurt the host. Evidence gathered so far suggests that obstacle can be overcome, though. One example is a drug based on my group's research with our University of British Columbia colleague Robert Hancock into host defense peptides: small proteins produced by innate immune cells in response to pathogens. Some of these directly penetrate microbial cell membranes to kill the intruder; others act as signaling molecules to call for immune cell reinforcements. A peptide we discovered, called IDR-1, is in the latter group. It induces dendritic cells to emit chemical signals calling for macrophages to battle pathogens but does not induce the dendritic cells to send out certain types of signals—substances such as tumor necrosis factor-alpha—that can cause a cascade of runaway inflammation. In fact, in animal trials, the molecule reduced inflammation while increasing the response of desirable immune cells to the site of infection.

Turnabout is fair play, and if microbes can learn to manipulate human immune cells' signaling, certainly people can do the same. As scientists' knowledge about how bacteria cause disease has grown exponentially over the past two decades, the sophistication of microbial virulence mechanisms has become increasingly apparent. Pathogens have evolved along with their hosts, fine-tuning their tool kits to an extraordinary degree. But just as the microbes have an impressive array of tricks up their proverbial sleeves, so do we. Studying the remarkable methods that bacteria use to invade and outwit hosts has improved understanding of immunity and disease processes as well. This growing understanding of host-pathogen-microbiota interactions is already allowing scientists to design new ways to prevent and treat bacterial infections—alternatives that cannot come too soon. ■

MORE TO EXPLORE

An Anti-infective Peptide That Selectively Modulates the Innate Immune Response. Monisha G. Scott et al. in *Nature Biotechnology,* Vol. 25, No. 4, pages 465–472; published online, March 25, 2007.

Manipulation of Host-Cell Pathways by Bacterial Pathogens. Amit P. Bhavsar, Julian A. Guttman and B. Brett Finlay in *Nature,* Vol. 449, pages 827–834; October 18, 2007.

Molecular Mechanisms of *Escherichia coli* Pathogenicity. Matthew A. Croxen and B. Brett Finlay in *Nature Reviews Microbiology;* published online, December 7, 2009.

FIXING THE GLOBAL Nitrogen Problem

Humanity depends on nitrogen to fertilize croplands, but growing global use is damaging the environment and threatening human health. How can we chart a more sustainable path? **By Alan R. Townsend and Robert W. Howarth**

KEY CONCEPTS

- Nitrogen pollution from smokestacks, tailpipes and heavily fertilized croplands creates a host of challenges for the environment and human health.
- Such ills are mounting as some countries burn more fossil fuels and pursue fertilizer-intensive endeavors, such as biofuels production.
- Synthetic fertilizer remains indispensable for meeting global food demands, but the world can—and should—do more with less.

—The Editors

Billions of people today owe their lives to a single discovery now a century old. In 1909 German chemist Fritz Haber of the University of Karlsruhe figured out a way to transform nitrogen gas—which is abundant in the atmosphere but nonreactive and thus unavailable to most living organisms—into ammonia, the active ingredient in synthetic fertilizer. The world's ability to grow food exploded 20 years later, when fellow German scientist Carl Bosch developed a scheme for implementing Haber's idea on an industrial scale.

Over the ensuing decades new factories transformed ton after ton of industrial ammonia into fertilizer, and today the Haber-Bosch invention commands wide respect as one of the most significant boons to public health in human history. As a pillar of the green revolution, synthetic fertilizer enabled farmers to transform infertile lands into fertile fields and to grow crop after crop in the same soil without waiting for nutrients to regenerate naturally. As a result, global population skyrocketed from 1.6 billion to six billion in the 20th century.

But this good news for humanity has come at a high price. Most of the reactive nitrogen we make—on purpose for fertilizer and, to a lesser extent, as a by-product of the fossil-fuel combustion that powers our cars and industries—does not end up in the food we eat. Rather it migrates into the atmosphere, rivers and oceans, where it makes a Jekyll and Hyde style transformation from do-gooder to rampant polluter. Scientists have long cited reactive nitrogen for creating harmful algal blooms, coastal dead zones and ozone pollution. But recent research adds biodiversity loss and global warming to nitrogen's rap sheet, as well as indications that it may elevate the incidence of several nasty human diseases.

Today humans are generating reactive nitrogen and injecting it into the environment at an accelerating pace, in part because more nations are vigorously pursuing such fertilizer-intensive endeavors as biofuel synthesis and meat production (meat-intensive diets depend on massive growth of grain for animal feed). Heavy fertilizer use for food crops and unregulated burning of fossil fuels are also becoming more prevalent in regions such as South America and Asia. Not surprisingly, then, dead zones and other nitrogen-related problems that were once confined to North America and Europe are now popping up elsewhere.

At the same time, fertilizer is, and should be,

BLAIR BRADSHAW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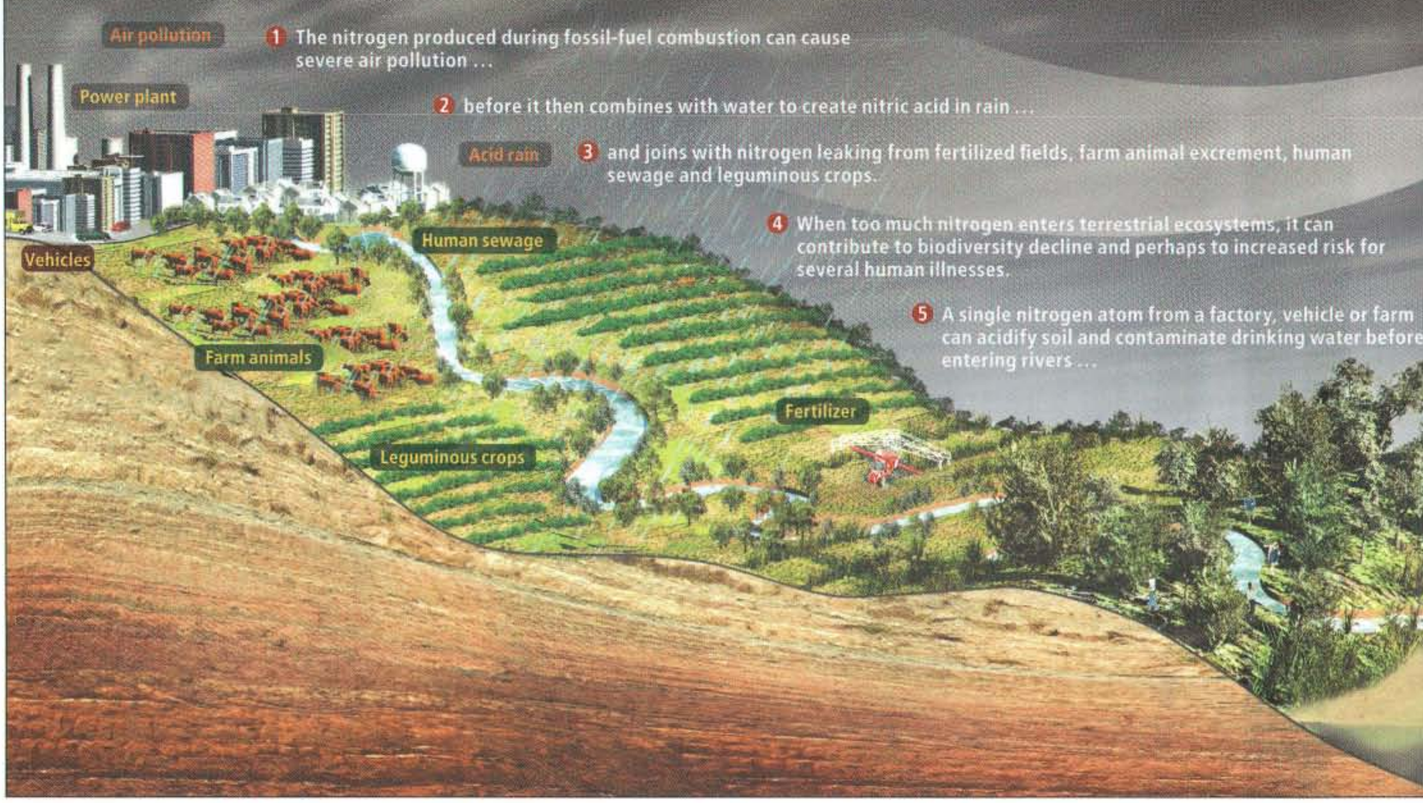
[NEED TO KNOW]

Nitrogen's Dark Side

Doubled up as N_2 gas, the most abundant component of the earth's atmosphere, nitrogen is harmless. But in its reactive forms, which emanate from farms and fossil-fuel-burning factories and vehicles, nitrogen can have a hand in a wide range of problems for the environment and human health.



DON FOLEY

The world is capable of growing MORE FOOD with LESS FERTILIZER.

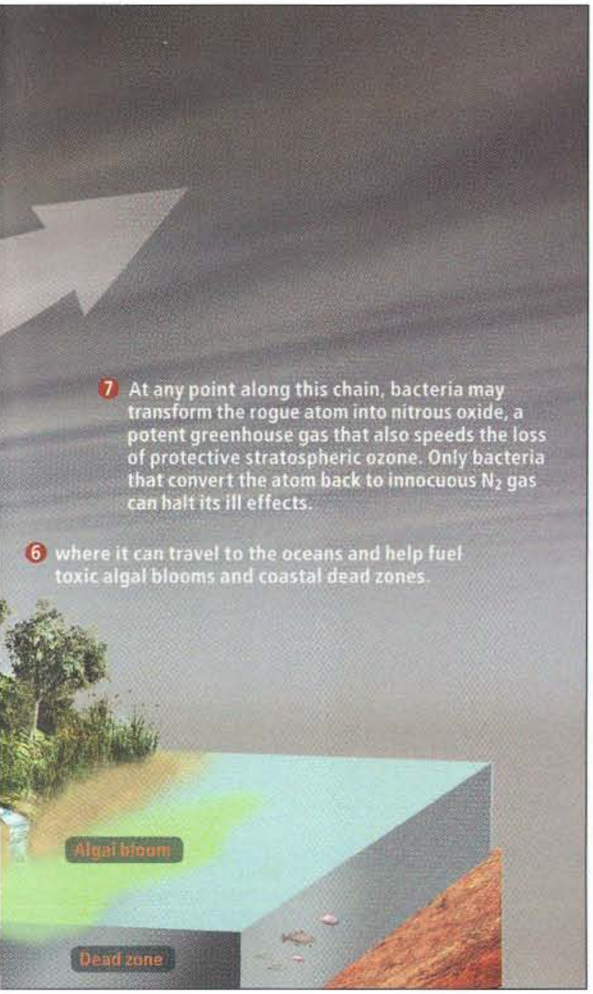
a leading tool for developing a reliable food supply in sub-Saharan Africa and other malnourished regions. But the international community must come together to find ways to better manage its use and mitigate its consequences worldwide. The solutions are not always simple, but nor are they beyond our reach.

Too Much of a Good Thing

Resolving the nitrogen problem requires an understanding of the chemistry involved and a sense of exactly how nitrogen fosters environmental trouble. The element's ills—and benefits—arise when molecules of N_2 gas break apart. All life needs nitrogen, but for the vast majority of organisms, the biggest reservoir—the atmosphere—is out of reach. Although 78 percent of the atmosphere consists of N_2, that gas is inert. Nature's way of making nitrogen available for life relies on the action of a small group of bacteria that can break the triple bond between those two nitrogen atoms, a process known as nitrogen fixation. These specialized bacteria exist in free-living states on land and in both freshwater and saltwater and in symbiotic relationships with the roots of legumes, which constitute some the world's most important crops. Another small amount of nitrogen gas is fixed when lightning strikes and volcanic eruptions toast it.

Before humanity began exploiting Haber-Bosch and other nitrogen-fixation techniques, the amount of reactive nitrogen produced in the world was balanced by the activity of another small bacterial group that converts reactive nitrogen back to N_2 gas in a process called denitrification. In only one human generation, though, that delicate balance has been transformed completely. By 2005 humans were creating more than 400 billion pounds of reactive nitrogen each year, an amount at least double that of all natural processes on land combined [*see top illustration on page 54*].

At times labeled nature's most promiscuous element, nitrogen that is liberated from its nonreactive state can cause an array of environmental problems because it can combine with a mul-



titude of chemicals and can spread far and wide. Whether a new atom of reactive nitrogen enters the atmosphere or a river, it may be deposited tens to hundreds of miles from its source, and even some of the most remote corners of our planet now experience elevated nitrogen levels because of human activity. Perhaps most insidious of all: a single new atom of reactive nitrogen can bounce its way around these widespread environments, like a felon on a crime spree.

Reaping the Consequences

When nitrogen is added to a cornfield or to a lawn, the response is simple and predictable: plants grow more. In natural ecosystems, however, the responses are far more intricate and frequently worrisome. As fertilizer-laden river waters enter the ocean, for example, they trigger blooms of microscopic plants that consume oxygen as they decompose, leading later to so-called dead zones. Even on land, not all plants in a complex ecosystem respond equally to nitrogen subsidies, and many are not equipped for a sudden embarrassment of riches. Thus, they lose out to new species that are more competitive in a nutrient-rich world. Often the net effect is a loss of biodiversity. For example, grasslands across much of Europe have lost a quarter or more of their plant species after decades of human-created nitrogen deposition from the atmosphere. This problem is so widespread that a recent scientific assessment ranked nitrogen pollution as one of the top three threats to biodiversity around the globe, and the United Nations Environment Program's Convention on Biological Diversity considers reductions of nitrogen deposition to be a key indicator of conservation success.

The loss of a rare plant typically excites little concern in the general public or among those who forge policy. But excess nitrogen does not just harm other species—it can threaten our own. A National Institutes of Health review suggests that elevated nitrate concentrations in drinking water—often a product of water pollution from the high nitrate levels in common fertilizers—may contribute to multiple health problems, including several cancers. Nitrogen-related air pollution, both particulates and ground-level ozone, affects hundreds of millions of people, elevating the incidence of cardiopulmonary ailments and driving up overall mortality rates.

Ecological feedbacks stemming from excess nitrogen (and another ubiquitous fertilizer chemical, phosphorus) may be poised to hit us with a slew of other health threats as well. How big or varied such responses will become remains to be seen, but scientists do know that enriching ecosystems with nitrogen changes their ecology in myriad ways. Recent evidence suggests that excess nitrogen may increase risk for Alzheimer's disease and diabetes if ingested in drinking water. It may also elevate the release of airborne allergens and promote the spread of certain infectious diseases. Fertilization of ragweed elevates pollen production from that notorious source, for instance. Malaria, cholera, schistosomiasis and West Nile virus show the potential to infect more people when nitrogen is abundant.

These and many other illnesses are controlled by the actions of other species in the environment, particularly those that carry the infective agent—for example, mosquitoes spread the malaria parasite, and snails release schistosomes into water. Snails offer an example of how nitrogen can unleash a chain reaction: more nitrogen or phosphorus run-off fuels greater plant growth in water bodies, in turn creating more food for the snails and a larger, faster-growing population

FAST FACTS

More than half the synthetic nitrogen fertilizer ever produced was applied in the past 20 years.

The production of synthetic nitrogen has skyrocketed 80 percent since 1960, dwarfing the 25 percent increase in atmospheric carbon dioxide over that same period.

If Americans were to switch to a typical Mediterranean diet, the country's fertilizer use would be cut in half.

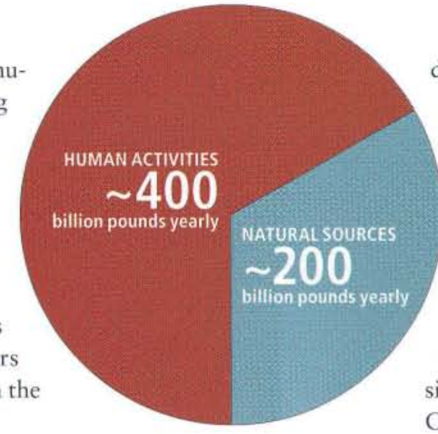
[THE AUTHORS]

Alan R. Townsend is incoming director of the Environmental Studies Program at the University of Colorado at Boulder and is a professor in the university's Institute of Arctic and Alpine Research and department of ecology and evolutionary biology. He studies how changes in climate, land use and global nutrient cycles affect the basic functioning of terrestrial ecosystems. Robert W. Howarth, who is David R. Atkinson Professor of Ecology and Environmental Biology at Cornell University, studies how human activities alter ecosystems, with an emphasis on freshwater and marine locales.

COURTESY OF ALAN R. TOWNSEND (*Townsend*); COURTESY OF ROXANNE MARINO (*Howarth*)

of these disease-bearing agents. The extra nutrients also fuel an exponentially increasing effect of having each snail produce more parasites. It is too soon to tell if, in general, nutrient pollution will up the risk of disease—in some cases, the resulting ecological changes might lower our health risks. But the potential for change, and thus the need to understand how it will play out, is rising rapidly as greater use of fertilizers spreads to disease-rich tropical latitudes in the coming decades.

Mounting evidence also blames reactive nitrogen for an increasingly important role in climate change. In the atmosphere, reactive nitrogen leads to one of its major unwanted byproducts—ground-level ozone—when it occurs as nitric oxide (NO) or as nitrogen dioxide (NO_2), collectively known as NO_x. Such ozone formation is troubling not only because of its threat to human health but also because at ground level, ozone is a significant greenhouse gas. Moreover, it damages plant tissues, resulting in billions of dollars in lost crop production every year. And by inhibiting growth, ozone curtails plants' ability to absorb carbon



Synthetic fertilizer, fossil-fuel combustion, industrial uses of ammonia (plastics, explosives, etc.), cultivation of soybeans and other leguminous crops

Nitrogen-fixing bacteria on land, lightning, volcanoes

HUMAN ACTIVITIES have tripled the amount of reactive nitrogen released into terrestrial environments and coastal oceans every year.

dioxide (CO_2) and offset global warming.

Reactive nitrogen is an especially worrisome threat to climate change when it occurs as nitrous oxide (N_2O)—among the most powerful of greenhouse gases. One molecule of N_2O has approximately 300 times the greenhouse warming potential of one molecule of CO_2. Although N_2O is far less abundant in the atmosphere than CO_2 is, its current atmospheric concentration is responsible for warming equivalent to 10 percent of CO_2's contribution. It is worth noting that excess nitrogen can at times counteract warming—by combining with other airborne compounds to form aerosols that reflect incoming radiation, for example, and by stimulating plants in nitrogen-limited forests to grow faster and thus scrub more CO_2 out of the atmosphere. But despite uncertainties regarding the balance between nitrogen's heating and cooling effects, most signs indicate that continued human creation of excess nitrogen will speed climate warming.

What to Do

Although fertilizer production accounts for much of the nitrogen now harming the planet—

MELISSA THOMAS (pie chart); DON FOLEY (map)

[GLOBAL PERSPECTIVES]

Shifting Hotspots

Regions of greatest nitrogen use (*red*) were once limited mainly to Europe and North America. But as new economies develop and agricultural trends shift, patterns in the distribution of nitrogen are changing rapidly. Recent growth rates in nitrogen use are now much higher in Asia and in Latin America, whereas other regions—including much of Africa—suffer from fertilizer shortages.

SOUTHERN BRAZIL: Rapid population growth and industrialization around Sao Paulo, poor civic sewage treatment and vibrant sugar cane production all contribute to this new South American nitrogen hotspot.

NORTH CHINA PLAIN: More vigorous application of fertilizer has produced stunning increases in maize and wheat production, but China now has the highest fertilizer inputs in the world.

roughly two thirds of that fixed by humans—abandoning it certainly is not an option. Fertilizer is too important for feeding the world. But an emphasis on efficient use has to be a part of the solution, in both the wealthy and the developing nations.

BIOFUELS FRENZY: Corn-based biofuels and their fertilizer-intensive production may contribute more to global warming than they alleviate in fossil-fuel savings.

Wealthy countries have blazed a path to an agricultural system that is often exceptionally nitrogen-intensive and inefficient in the use of this key resource. Too often their use of nitrogen has resembled a spending spree with poor returns on the investment and little regard for its true costs. Elsewhere, a billion or more people stand trapped in cycles of malnutrition and poverty. Perhaps best exemplified by sub-Saharan Africa, these are regions where agricultural production often fails to meet even basic caloric needs, let alone to provide a source of income. Here an infusion of nitrogen fertilizers would clearly improve the human condition. Recent adoption of policies to supply affordable fertilizer and better seed varieties to poor farmers in Malawi, for example, led to substantial increases in yield and reductions in famine.

But this fertilizer does not need to be slathered on injudiciously. The proof is out there: studies from the corn belt of the U.S. Midwest to the wheat fields of Mexico show that overfertilization has been common practice in the breadbaskets of the world—and that less fertilizer often does not mean fewer crops. The simple fact is that as a whole, the world is capable of growing more food with less fertilizer by changing the farming practices that have become common in an era of cheap, abundant fertilizer and little regard for the long-term consequences of its use. Simply reducing total application to many crops is an excellent starting point; in many cases, fertilizer doses are well above the level needed to ensure maximum yield in most years, resulting in disproportionately large losses to the environment. In the U.S., people consume only a little more than 10 percent of what farmers apply to their fields every year. Sooner or later, the rest ends up in the environment. Estimates vary, but for many of our most common crops, a quarter to half immediately runs off the field with rainwater or works its way into the atmosphere.

IT'S UP TO YOU

Making certain personal choices will reduce your carbon and nitrogen footprints simultaneously:

- Support wind power, hybrid cars and other policies designed to reduce fossil-fuel consumption.
- Choose grass-fed beef and eat less meat overall.
- Buy locally grown produce.

Precision farming techniques can also help. Applying fertilizer near plant roots only at times of maximum demand is one example of methods that are already in play in some of the wealthier agricultural regions of the planet. By taking advantage of Global Positioning System technology to map their fields, coupled with remotely sensed estimates of plant nutrient levels, farmers can refine calculations of how much fertilizer a crop needs and when. But the high-tech equipment is costly, prohibitively so for many independent farmers, and so such precision farming is not a panacea.

The solutions are not all high tech. Cheaper but still effective strategies can include planting winter cover crops that retain nitrogen in a field instead of allowing a field to lie bare for months, as well as maintaining some form of plant cover in between the rows of high-value crops such as corn. Simply applying fertilizer just before spring planting, rather than in the fall, can also make a big difference.

The world can also take advantages of changes in meat production. Of the nitrogen that ends up in crop plants, most goes into the mouths of pigs, cows and chickens—and much of that is then expelled as belches, urine and feces. Although a reduction in global meat consumption would be a valuable step, meat protein will remain an important part of most human diets, so efficiencies in its production must also improve. Changing animal diets—say, feeding cows more grass and less corn—can help on a small scale, as can better treatment of animal waste, which, like sewage treatment facilities for human waste, converts more of the reactive nitrogen back into inert gas before releasing it into the environment [see "The Greenhouse Hamburger," by Nathan Fiala; SCIENTIFIC AMERICAN, February 2009].

On the energy side, which represents about 20 percent of the world's excess nitrogen, much reactive nitrogen could be removed from current fossil-fuel emissions by better deployment of

NO_X-scrubbing technologies in smokestacks and other sources of industrial pollution. Beyond that, a sustained global effort to improve energy efficiency and move toward cleaner, renewable sources will drop nitrogen emissions right alongside those for carbon. Removing the oldest and least-efficient power plants from production, increasing vehicle emission standards and, where possible, switching power generation from traditional combustion to fuel cells would all make a meaningful difference.

Of course, one source of renewable energy—biofuel made from corn—is generating a new demand for fertilizer. The incredible increase in the production of ethanol from corn in the U.S.—a nearly fourfold rise since 2000—has already had a demonstrable effect on increased nitrogen flows down the Mississippi River, which carries excess fertilizer to the Gulf of Mexico, where it fuels algal blooms and creates dead zones. According to a report last April by the Scientific Committee on Problems of the Environment (then part of the International Council for Science), a business-as-usual approach to biofuel production could exacerbate global warming, food security threats and human respiratory ailments in addition to these familiar ecological problems.

How to Get It Done

Society already has a variety of technical tools to manage nitrogen far more effectively, retaining many of its benefits while greatly reducing the risk. As for our energy challenges, a switch to more sustainable nitrogen use will not come easily, nor is there a silver bullet. Furthermore, technological know-how is not enough: without economic incentives and other policy shifts, none of these solutions will likely solve the problem.

The speed at which nitrogen pollution is rising throughout the world suggests the need for some regulatory control. Implementing or strengthening environmental standards, such as setting total maximum daily loads that can enter surface waters and determining the reactive nitrogen concentrations allowable in fossil-fuel emissions, is probably essential. In the U.S. and other nations, regulatory policies are being pursued at both national and regional scales, with some success [see "Reviving Dead Zones," by Laurence Mee; SCIENTIFIC AMERICAN, November 2006]. And as much needed policy changes bring fertilizer to those parts of the world largely bypassed by the green revolution, those areas should employ sustainable solutions from the outset—to avoid repeating mistakes made in the U.S. and elsewhere.

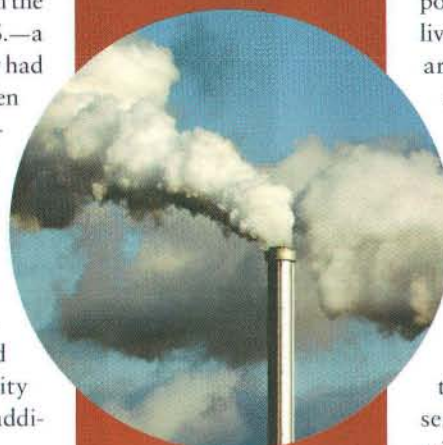
Promising improvements could occur even without the regulatory threat of monetary fines for exceeding emissions standards. Market-based instruments, such as tradable permits, may also be useful. This approach proved remarkably successful for factory emissions of sulfur dioxide. Adoption of similar approaches to NO_X pollution are already under way, including the U.S. Environmental Protection Agency's NO_X Budget Trading Program, which began in 2003. Such policies could be extended to fertilizer runoff and livestock emissions as well—although the latter are more difficult to monitor than the smokestacks of a coal-burning power plant.

Other approaches to the problem are also beginning to take hold, including better use of landscape design in agricultural areas, especially ensuring that crop fields near bodies of water are fringed by intervening wetlands that can markedly reduce nitrogen inputs to surface waters and the coastal ocean. Protected riparian areas, such those promoted by the U.S. Conservation Reserve Program, can do double duty: not only will they reduce nitrogen pollution, but they also provide critical habitat for migratory birds and a host of other species.

Substantial progress may also require a rethinking of agricultural subsidies. In particular, subsidies that reward environmental stewardship can bring about rapid changes in standard practice. A recent not-for-profit experiment run by the American Farmland Trust shows promise. Farmers agreed to reduce their fertilizer use and directed a portion of their cost savings from lowered fertilizer purchases to a common fund. They then fertilized the bulk of the crop at reduced rates, while heavily fertilizing small test plots. If such plots exceeded the average yield of the entire field, the fund paid out the difference.

As one of us (Howarth) reported in a Millennium Ecosystem Assessment in 2005, such payouts would rarely be required, given the current tendency to overfertilize many crops. The average farmer in the breadbasket of the upper U.S. Midwest (the source of the great majority of nitrogen pollution fueling the Gulf of Mexico dead zones) typically uses 20 to 30 percent more nitrogen fertilizer than agricultural extension agents recommend. As predicted, farmers who participated in this and similar experiments have applied less fertilizer with virtually no de-

SOLUTIONS ARE WITHIN REACH



- Industry can install more NO_x-scrubbing technologies in smokestacks and other sources of pollution.
- Farmers can use less fertilizer. For many crops, applying less fertilizer would not sacrifice yield.
- Community officials can ensure that crop fields are fringed by wetlands that can absorb nitrogen-laden runoff before it enters streams or lakes.
- Nations can institute farm subsidies that reward environmental stewardship.

PHILIPPE LISSAC Godong/Corbis

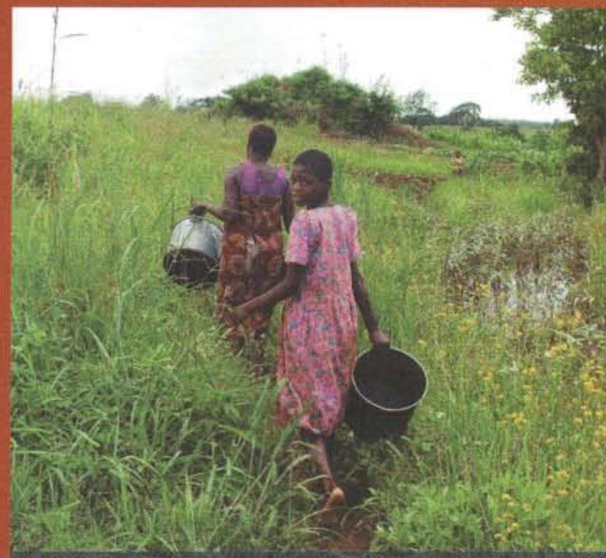
[COUNTERPOINT]

Where Fertilizer *Shortage* Is the Problem

Synthetic fertilizer has been, and will continue to be, critical to meeting world food demands, particularly in malnourished regions, such as sub-Saharan Africa, where increased fertilizer use is one of the leading strategies for developing a reliable food supply.

Humans already produce more than enough fertilizer to feed the world, but inequitable and inefficient distribution means that excessive use is causing problems in some places while poverty-stricken regions are mired in a cycle of malnutrition. Making synthetic fertilizer available to those who typically cannot afford it has clearly played a role in bettering food security and the human condition in parts of rural sub-Saharan Africa, where widespread malnutrition stems directly from nutrient depletion and soil erosion.

Fertilizer subsidies are one pillar of the African Millennium Villages Project, an ambitious proof-of-concept project in which coordinated efforts to improve health, education and agricultural productivity are now under way in a series of rural villages across Africa. Launched in 2004, the project was implemented on a national scale in Malawi. After a decade of repeated food shortages and famine, Malawi created subsidies that provided poor farmers with synthetic fertilizer and improved seed varieties. Although better climate conditions played a role, the approach clearly worked: Malawi went from a 43 percent food deficit in 2005 to a 53 percent surplus in 2007. *—A.R.T. and R.W.H.*



SYNTHETIC FERTILIZER remains critical in Mwandama, Malawi.

RON HAVIV VII/AP Photo

crease in crop yield and have saved money as a result, because what they paid into the fund is less than the amount they saved by buying less fertilizer. As a result, such funds grow with no taxpayer subsidy.

Finally, better public education and personal choice can play critical roles. In much the way that many individuals have begun reducing their own energy consumption, so, too, can people from all walks of life learn how to select a less nitrogen-intensive lifestyle.

One big improvement would be for Americans to eat less meat. If Americans were to switch to a typical Mediterranean diet, in which average meat consumption is one sixth of today's U.S. rates, not only would Americans' health improve, the country's fertilizer use would be cut in half. Such shifts in dietary and agricultural practices could simultaneously lower environmental nitrogen pollution and improve public health: nitrogen-intensive agricultural practices in wealthier nations contribute to overly protein-rich, often unbalanced diets that link to health concerns from heart disease and diabetes to childhood obesity.

Making personal choices designed to reduce an individual's carbon footprint can help—not just on the industrial side, as in supporting wind power and hybrid cars, but on the agricultural side as well. Eating less meat, eating locally grown food and eating grass-fed rather than corn-fed beef all tackle the carbon and nitrogen problems simultaneously. Individual choices alone are unlikely to solve the problems, but history shows they can spur societies to move down new paths. The well-known trade-offs between climate and energy production that were long ignored as hypothetical now appear everywhere from presidential speeches to roadside billboards to budding regulatory schemes.

Unfortunately, the nitrogen problem is in one critical way tougher than the carbon problem. In solving the latter, it is reasonable to work toward a future of one day producing energy without CO_2-emitting fossil fuels. But it is not possible to envision a world free of the need to produce substantial amounts of reactive nitrogen. Synthetic fertilizer has been, and will continue to be, critical to meeting world food demands. Yet if we stay on a business-as-usual trajectory, with nitrogen production continuing to rise, we will face a future in which the enormous benefits of Fritz Haber's discovery become ever more shrouded by its drawbacks.

Still, as we have argued here, nitrogen cycle problems could be significantly reduced with current technology at relatively affordable costs. We can and must do better. It will take immediate and ongoing effort, but a sustainable nitrogen future is entirely achievable. ■

➡ MORE TO EXPLORE

Nutrient Management. R. W. Howarth et al. in *Ecosystems and Human Well-Being: Policy Responses*. Millennium Ecosystem Assessment. Island Press, 2005.

Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions. James N. Galloway et al. in *Science*, Vol. 320, pages 889–892; May 16, 2008.

Biofuels: Environmental Consequences and Interactions with Changing Land Use. Edited by R. W. Howarth and S. Bringezu. *Proceedings of the SCOPE International Biofuels Project Rapid Assessment*, Cornell University, April 2009. **http://cip.cornell.edu/biofuels**

Nutrient Imbalances in Agricultural Development. P. M. Vitousek et al. in *Science*, Vol. 324, pages 1519–1520; June 19, 2009.

Seeing Forbidden Colors

Engineers often load a structure with weight until it collapses or shake it until it flies apart. Like engineers, many scientists also have a secret love for destructive testing—the more catastrophic the failure, the better. Human vision researchers avoid irreversible failures (and lawsuits) but find reversible failures fascinating and instructive—and sometimes even important, as with the devastating spatial disorientations and visual blackouts that military pilots can experience. At the U.S. Air Force Research Laboratory, the two of us explore the most catastrophic visual failures we can arrange. We create conditions in which people see images flowing like hot wax and fragmenting like a shattered mosaic. Here, we tell the story of the two most intriguing perceptual breakdowns we have studied: forbidden colors and biased geometric hallucinations.

Have you ever seen the color bluish yellow? We do not mean green. Some greens may appear bluish and others may appear yellow-tinged, but no green (or any other color) ever appears both bluish and yellowish at the same moment. And have you ever seen reddish green? We do not mean the muddy brown that might come from mixing paints, or the yellow that comes from combining red and green light, or the texture of a pointillist's field of red and green dots. We mean a single color that looks reddish and greenish at the same time, in the same place.

By arranging the right conditions, we have seen these unimaginable, or "forbidden," colors, as have our experimental subjects. And we have found ways to control, or bias, the hallucinatory patterns of concentric circles and wheel spokes that people can see in rapidly flickering light—although the bias worked opposite to our expectations. Both these phenomena reveal something new about the neural basis of opponency, one of the oldest concepts in the science of perception.

Opponency is ubiquitous in physiology. For example, to bend your arm, you relax your triceps while contracting your biceps; biceps and triceps are opponent muscles, in that they act in direct

JEN CHRISTIANSEN

People can be made to see reddish green and yellowish blue—colors forbidden by theories of color perception. These and other hallucinations provide a window into the phenomenon of visual opponency

BY VINCENT A. BILLOCK AND BRIAN H. TSOU

opposition to each other. In 1872 German physiologist Ewald Hering suggested that color vision was based on opponency between red and green and between yellow and blue; at each spot in the visual field, the redness and greenness muscles, so to speak, opposed each other. Perception of redness at a spot precluded perception of greenness there, and vice versa, just as you cannot simultaneously bend and straighten your arm. All the hues that people do see could be made by combining red or green with yellow or blue. Hering's theory explained why humans can perceive blue and green together in turquoise, red and yellow together in orange, and so on, but never red with green or blue with yellow in the exact same time and place.

Crazy Colors

The observation that people never see mixtures of opponent colors has been one of the most secure in cognitive science. Research has suggested, moreover, that color opponency begins in the retina and the midbrain—the first brain region involved in vision—with nerves carrying data that amount to one color signal subtracted from another. The raw color signals originate with cone cells in the retina, which detect light in three overlapping bands of wavelengths. Other cells add and subtract the outputs from the three kinds of cone cells, producing signals relating to four primary colors—red, green, yellow and blue. But it is as if the visual system is wired with two data channels for color: a red-minus-green channel (in which positive signals represent levels of redness, negative signals represent greenness and zero signal represents neither) and a similarly operating yellow-minus-blue channel. Such hardwiring enforces Hering's laws of color opponency.

In 1983, however, Hewitt D. Crane and Thomas P. Piantanida of SRI International in Menlo Park, Calif., reported a way to dodge the perceptual rules that forbid such colors as reddish green and yellowish blue. They had their subjects look at side-by-side fields of red and green or yellow and blue. Their apparatus tracked their subjects' eye positions and moved mirrors to keep the color fields stabilized—that is, frozen in place on each subject's retina despite all the continual little movements of the eye. Image stabilization can lead to many interesting effects, such as an image seeming to break into pieces that wax and wane in visibility. Of particular interest to Crane and Piantanida was the propensity for borders to fade in stabilized images.

Indeed, their experimental subjects saw the border between the two opponent colors evaporate; the colors flowed and mixed across the vanishing border. Some subjects reported seeing the forbidden reddish greens and yellowish blues. Others saw hallucinatory textures, such as blue glitter on a yellow background.

Crane and Piantanida's article should have provoked widespread interest: two highly competent investigators were reporting a major violation of the best-established psychophysical law. Instead the paper became the study that vision researchers did not talk about—the Crazy Old Aunt in the Attic of Vision.

We think four reasons contributed to this negligence. First, the result was inconsistent: some subjects saw the hallucinatory textures instead of forbidden colors. Second, the forbidden colors were hard to describe. Crane and Piantanida tried to get around this problem by having artists describe the colors. It did not help. Third, the experiment was hard to replicate. Crane had invented their special eye tracker, and it was expensive and difficult to use. Finally, researchers had no theoretical basis for understanding the result. We are convinced this was the crucial obstacle—

KEY CONCEPTS

- Red and green are called opponent colors because people normally cannot see redness and greenness simultaneously in a single color. The same is true for yellow and blue.
- Researchers have long regarded color opponency to be hardwired in the brain, completely forbidding perception of reddish green or yellowish blue.
- Under special circumstances, though, people can see the "forbidden" colors, suggesting that color opponency in the brain has a softwired stage that can be disabled.
- In flickering light, people see a variety of geometric hallucinations with properties suggestive of a geometric opponency that pits concentric circles in opposition to fan shapes.

—The Editors

[COLOR EXPERIMENT]

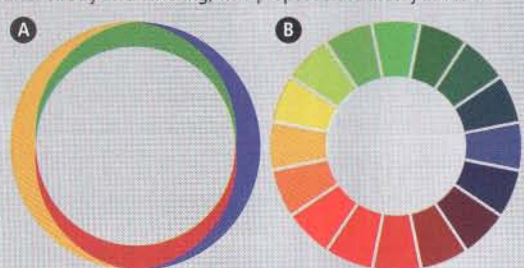
SEEING HUES OLD AND NEW

The authors showed that the cognitive phenomenon of color opponency (*below*) can be suspended to allow perception of colors not normally seen (*opposite page*).

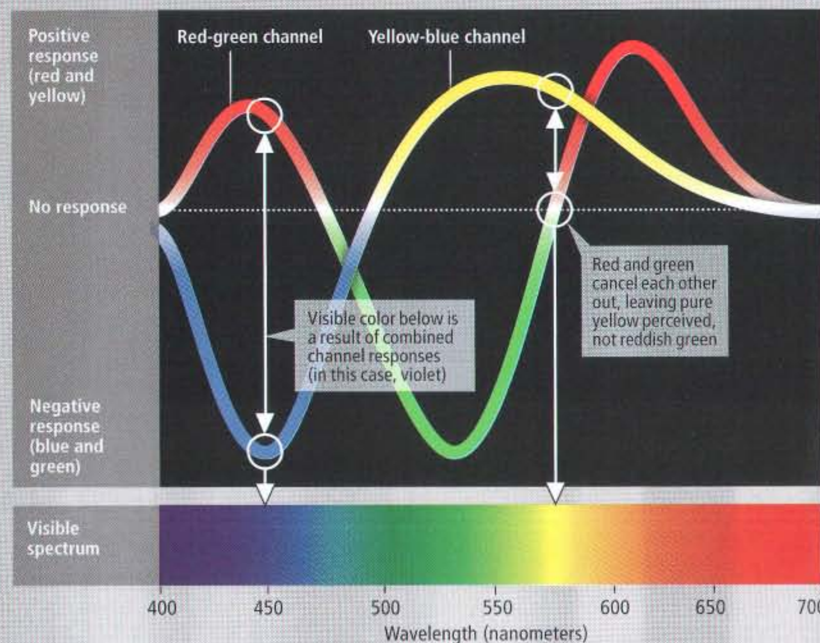
HOW COLOR OPPONENCY WORKS

Human color vision seems to be based on two pairs of colors known as opponent colors: yellow and blue; red and green. Perception of one member of a pair (say, yellow) somewhere in the visual field usually precludes perception of the opponent color (blue) at that spot at the same time. Hence, although people routinely see colors that combine other colors—such as purple appearing to mix red and blue—we usually cannot see yellowish blue or reddish green. Our visual system seems to use two channels for color information (*right*): a yellow-minus-blue channel, which can signal yellowness or blueness but not both, and a red-minus-green channel.

▼ Blending various amounts of yellow or blue with red or green (*a*) produces all the hues we see (*b*). This illustration is modeled after one by Ewald Hering, who proposed the theory in 1897.



▼ How the visual system's two color channels respond to light explains the spectrum's appearance—why violet light looks reddish blue, for instance, and why yellow light does not look reddish green.



things that do not fit into the existing paradigm are hard to think about. Crane and Piantanida guessed that they had bypassed the part of the visual system responsible for color opponency and activated a perceptual filling-in mechanism, but they did not develop the idea.

Our Luminant Idea

Several years ago the two of us had an insight into a potential explanation for the varying perceptions of Crane and Piantanida's observers. We knew that, along with image stabilization, one other experimental condition leads to a similar loss of border strength: namely, when two adjacent colors have equal luminance. Luminance is similar but not identical to perceived brightness. Two colors are equiluminant to an observer if switching them very rapidly produces the least impression of flickering.

When subjects stare at two adjacent fields with equiluminant colors, they see the border between the colors weaken and disappear, allowing the colors to flow into each other—except in the case of red-green or yellow-blue pairs. We knew that this border-collapse effect is strongest when the observer minimizes eye movements. Perhaps the effects of equiluminance and stabilization would combine synergistically, leading to border collapse and color mixing powerful enough to happen consistently even with opponent colors. To test this idea, we teamed up with our Air Force Research Lab colleague Lt. Col. Gerald A. Gleason, who studied eye movements.

We anchored our subjects to Gleason's eye tracker using chinrests or bite bars to minimize head movement. We decided not to use artists and other laypeople as subjects. For this experiment we wanted vision researchers raised on color theory, skeptical about colors undreamt of in Hering's philosophy, and able to describe their observations in a rich shorthand of "visionese"—important when you are mumbling your observations through clenched teeth. And we wanted credible subjects who could testify to our incredulous colleagues. Thus, we recruited seven vision researchers (including Billock and Gleason) with normal color vision.

Because people vary in their perceptions of the luminance of different colors, we first measured our subjects' responses to red, green, yellow and blue. Then we showed each subject side-by-side fields of red and green or yellow and blue, with the colors customized to appear either equiluminant or strongly nonequiluminant.

[THE AUTHORS]

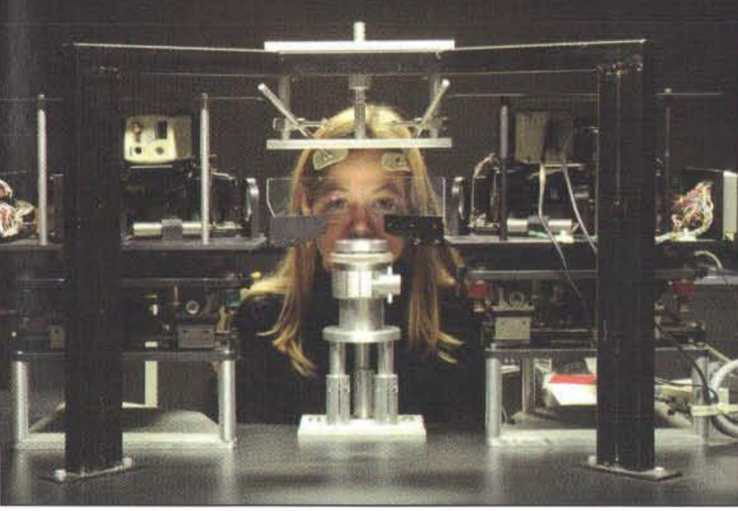
Vincent A. Billock and **Brian H. Tsou** are biophysicists who bring the perspective of complexity theory to problems in human color and spatial vision. They conduct research together at Wright-Patterson Air Force Base in Ohio. Billock is a lead scientist for General Dynamics in Dayton, Ohio. Tsou is a principal scientist at the U.S. Air Force Research Laboratory. Tsou *never* sees reddish green—he is red-green colorblind, a condition that motivated him to study color vision.

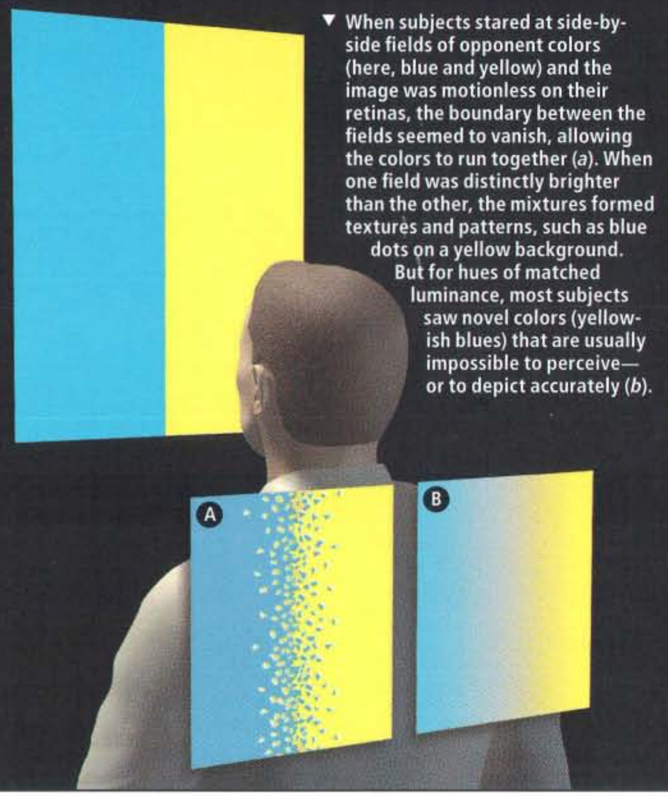
COURTESY OF GENERAL DYNAMICS, INC. (*Billock*); COURTESY OF BRIAN H. TSOU (*Tsou*); CATHERINE WILSON (*color wheels*); JEN CHRISTIANSEN (*spectrum graph*)

HOW TO SEE FORBIDDEN COLORS

The authors found unusual conditions that reliably overcame the prohibition against perceiving yellowish blue and reddish green. This result implies that color opponency in the brain is not as hardwired as is commonly thought. Apparently the opponency mechanism can be disabled.

▼ In forbidden color experiments an eye tracker monitors subjects' eye movements to keep the presented color stimuli in a fixed position on the retina.





▼ When subjects stared at side-by-side fields of opponent colors (here, blue and yellow) and the image was motionless on their retinas, the boundary between the fields seemed to vanish, allowing the colors to run together (*a*). When one field was distinctly brighter than the other, the mixtures formed textures and patterns, such as blue dots on a yellow background. But for hues of matched luminance, most subjects saw novel colors (yellowish blues) that are usually impossible to perceive—or to depict accurately (*b*).

COURTESY OF PETER DE GRAEF; EQUIPMENT PHOTOGRAPHED BY JOHAN VAN RENSBERGEN *Laboratory of Experimental Psychology, University of Leuven (experimental apparatus)*; GEORGE RETSECK *(blue/yellow experiment)*; JEN CHRISTIANSEN *(laptop)*

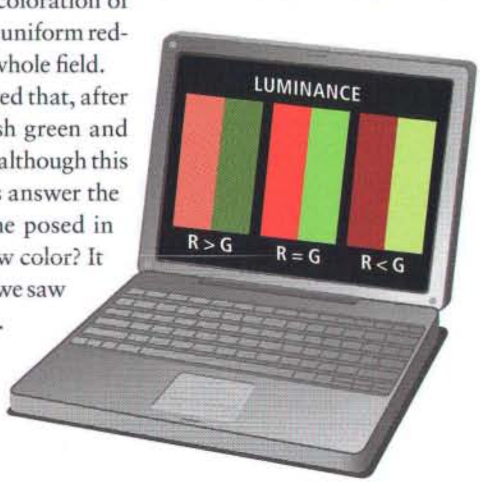
The combination of equiluminance and image stabilization was remarkably effective. For the equiluminant images, six out of our seven observers saw forbidden colors (the seventh observer's vision grayed out immediately every time). The border between the two colors would vanish, and the colors would flow across the border and mix. Sometimes the result looked like a gradient that ran from, say, red on the left to green on the right, with every possible shade of greenish red and reddish green in between. Other times we saw red and green fields in the same place but at different depths, as if seeing one hue through the other without any discoloration of either of them. Often we saw a nice, uniform reddish green or bluish yellow fill the whole field.

Intriguingly, two subjects reported that, after the exercise, they could see reddish green and bluish yellow in their imaginations, although this ability did not persist. We can thus answer the question philosopher David Hume posed in 1739: Is it possible to perceive a new color? It *is*—but the striking new colors that we saw were compounds of familiar colors.

Our observations led us to develop a model of how color opponency could arise in the brain without relying on hardwired subtraction. In our model, populations of neurons compete for the right to fire, just as two animal species compete for the same ecological niche—but with the losing neurons going silent, not extinct. A computer simulation of this competition reproduces classical color opponency well—at each wavelength, the "red" or "green" neurons may win, but not both (and similarly for yellow and blue). Yet if the competition is turned off by, say, inhibiting connections between the neural populations, the previously warring hues can coexist.

LUMINANCE

To see forbidden hues, it helps if you perceive the two displayed color fields to have equal luminance, which is similar to brightness. Two colors are equiluminant when swapping them very rapidly gives you the least sense of flickering. Depicting luminance on the printed page is difficult because people differ in their luminance perceptions, and printing introduces changes in the saturation of colors, along with the changes in brightness.



Tiger Stripes on the Brain

In our experiment, when the red-green or yellow-blue fields differed significantly in luminance we and our other subjects did not see forbidden colors. Instead we saw textures, such as green glitter on a red field or blue streaks on a yellow field, just as Crane and Piantanida reported for some of their subjects. They may have used colored images that were equiluminant for some subjects but markedly nonequiluminant for others.

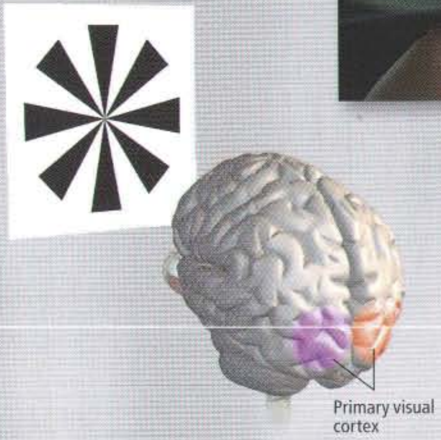
These illusory speckled and striped patterns that we saw were intriguing. The study of these kinds of patterns in other contexts has a rich history. Such patterns arise in certain mixtures of

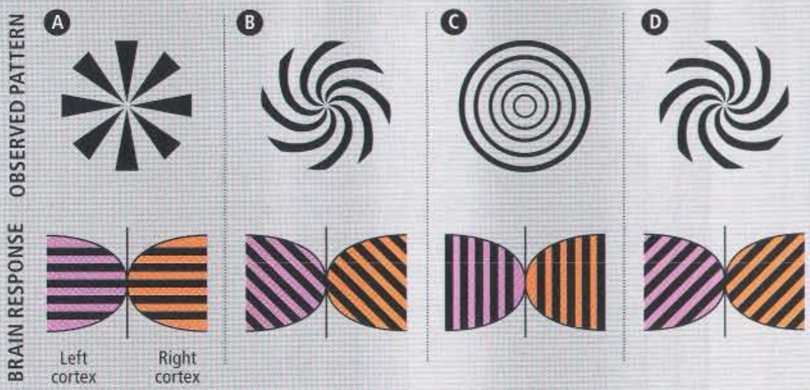
[GEOMETRY EXPERIMENT]

Controlled Hallucinations

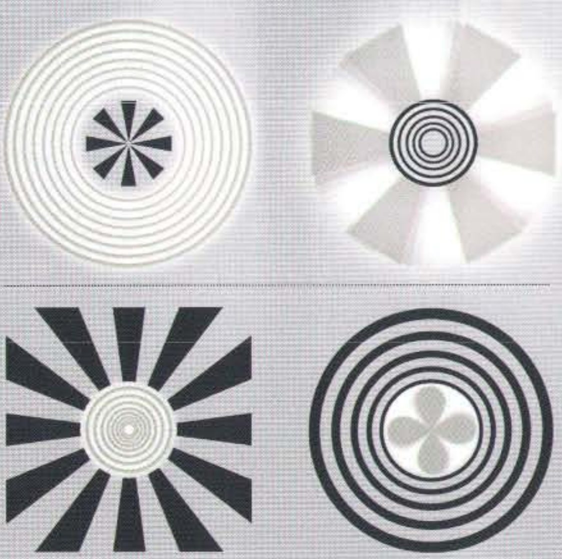
If you have ridden with your eyes closed in a car driven along a tree-lined street, you may have experienced "flicker," a rapid oscillation of light and dark. Flicker in a blank visual field (such as the backs of your eyelids) often induces fleeting hallucinations of geometric patterns, including concentric circles, spirals and fan shapes like spokes of a wheel. Study of brain processes uncovered by these illusions would be aided if researchers could stabilize the hallucinations and control which pattern a subject sees.

▼ Clues to the neural basis of flicker illusions are provided by the brain's response to real examples of the patterns. Many of the patterns trigger activity along stripes of neurons in the primary visual cortex (*right*). When a person looks at a real fan shape, horizontal stripes activate (*below, a*). Concentric circles excite vertical stripes (*c*), and spirals excite slanted stripes (*b, d*). Geometric hallucinations presumably arise when flicker stimulates the primary visual cortex and the excitations self-organize into patterns of stripes.





► To control people's flicker hallucinations, the authors showed subjects small patterns (*black*) and flickered the light in the surrounding blank area (*top*). Subjects saw hallucinations (*gray*) of circles around real fan shapes and rotating fan shapes around real circles. Similar effects occurred with a flickered blank area inside real patterns (*bottom*). These effects are analogous to a red region making an adjacent gray area seem tinted green (red's opponent color)—the circles and fan shapes act like "opponent" patterns.



reacting chemicals in which the chemicals diffuse asymmetrically or at different rates. English mathematician and computing pioneer Alan Turing introduced these reaction-diffusion systems as mathematical systems worthy of investigation, which can model the patterns seen in zebra coats, leopard skins and a variety of other biological phenomena—and in particular, hallucinations.

Visual hallucinations involving geometric patterns are generated by many triggers: drugs, migraines, epileptic seizures and—our favorite—a visual stimulus called empty-field flicker. David Brewster (inventor of the kaleidoscope) investigated flicker-induced hallucinations in the 1830s, reportedly experiencing them by dashing past a high sunlit fence with his eyes closed, which produced rapid flashes of light and dark ("flicker") on the empty canvas of the backs of his eyelids. Today it is easier—and safer—to replicate the effect by closing your eyes while a passenger in a car driven along a tree-lined street or, better yet, by looking at a flickering computer monitor.

Common geometric hallucinations produced by flicker include fan shapes, concentric circles, spirals, webs and honeycombs. In 1979 Jack D. Cowan of the University of Chicago and his Ph.D. student G. Bard Ermentrout (now at the University of Pittsburgh) noticed that all these images corresponded to excitation of striped patterns of neurons in the primary visual cortex, a region of the brain at the back of the head involved in visual processing. For example, when a person looks at an actual image of concentric circles, vertical stripes of neurons in the primary visual cortex are activated. A fan-shaped pattern, such as spokes of a wheel, excites horizontal rows of neurons. Spirals excite slanted stripes.

Thus, Ermentrout and Cowan could account for many of the reported geometric hallucinations if the visual cortex could spontaneously generate striped patterns of neural activity in re-

ALAIN DAUSSIN *Getty Images (girl in car)*; GEORGE RETSECK *(brain)*; CATHERINE WILSON *(geometric illusions)*

sponse to flicker. In 2001 Cowan and other coworkers extended the model to account for many more complicated patterns. These findings, however, do not offer a recipe for how to induce any particular hallucination for detailed study. Indeed, the patterns induced by flicker are both unpredictable and unstable, probably because each flash disturbs the previously elicited hallucination. Having a technique to evoke a specific stable hallucination for extended observation would be very helpful. Visual hallucinations and Turing's mathematics of pattern formation might then provide a window into the dynamics of the human visual system.

To try to stabilize the flicker-induced patterns, the two of us took inspiration from other spontaneous pattern-forming systems that can be made predictable by introducing a suitable bias. For instance, picture a shallow pan of oil, heated from below and cooled from above. If the temperature difference is great enough, the rising hot oil and falling cool oil self-organize into a pattern of horizontal cylinders, which from above look like stripes. Each cylinder rotates on its axis—fluid rising on one side and falling on the other. The pattern is stable if adjacent cylinders rotate in opposite directions, like cogwheels.

Ordinarily the orientation of the cylinders (the direction of the "stripes") is determined by chance while the pattern is forming, but if you inject an upwelling of fluid along a particular orientation, then the pattern of cylinders evolves to line up with it. Fortuitously misled by this analogy, we decided to see if presenting a pattern next to a flickering blank area would stabilize the hallucination seen by people. In experiments we displayed small circular and fan-shaped designs at a constant illumination with rapidly flashing light in the blank area around them. The physical patterns would excite stripes of a specific orientation in a person's visual cortex, and we expected the excitations induced by the flickering area would extend the pattern by adding parallel stripes. Thus, we thought our subjects would see the circular patterns and the fan shapes extended into the surrounding flickering area.

Circles and Fans

Much to our surprise, our subjects saw the opposite effect. The small physical circles were always surrounded by illusory fan shapes, which rotated at about one revolution per second. Conversely, flickering around small physical fan shapes evoked hallucinations of circular patterns, which occasionally pulsated. Similar results occurred when the physical pattern surrounded a flickering empty center. In all cases, the hallucination was confined to the flickering area—it extended through the physical pattern only if we made the physical pattern flicker on and off in synchrony with the light in the empty area.

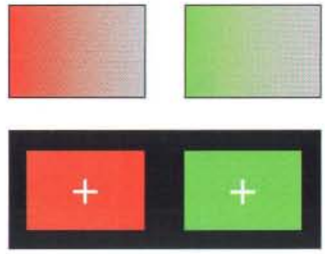
In retrospect this outcome should not have been surprising. Fifty years ago Donald M. MacKay of King's College London showed that when fan shapes are viewed in flickering light, a faint pattern of concentric rings can be seen overlaying the fan, and vice versa. MacKay's result can be interpreted as arising from a kind of opponency. To understand this point, consider what happens if you see a bright flash of red light: you see a green afterimage, green being the opponent color to red. If the visual system processes fan shapes and concentric circles as opponent geometric shapes, then the faint patterns seen in MacKay's illusion can be geometric afterimages present during the dark moments between the flashes.

Our new illusion also has a color analogue: a red field can make an adjacent gray field look greenish. Under the correct dynamic conditions—our flickering setup—a geometric pattern induces the opponent geometric pattern in the empty field next to it. Stated another way, MacKay's illusion involves geometric opponency separated in time (that is, the fans and circles are present at separate moments), whereas our effect is geometric opponency separated in space (the fans and circles being in adjacent regions).

Although it may be natural to regard forbidden colors and biased geometric hallucinations as parlor tricks, they illustrate important points about vision and the nature of perceptual opponencies. Forbidden colors reveal that color opponency—which has served as the model for all perceptual opponencies—is not as rigid and hardwired as psychologists thought. Softwired mechanisms such as our competition model may be needed to understand fully how the brain handles opponent colors.

Experiments that stabilize geometric hallucinations reveal that for all their exotic appearance, these hallucinations behave surprisingly like familiar visual effects involving colors. The neural nature of geometric opponencies is also very interesting. The opponent patterns involve perpendicular stripes of excited neurons in the visual cortex—could this feature be a clue to how the neural wiring produces the opponency? To answer this and other questions, researchers will have to come up with new ways to push the visual system to its breaking point and beyond. ■

CAN YOU SEE IT?



Binocular vision may provide a way to see forbidden colors. Try staring intently at these pairs of rectangles, allowing your eyes to go cross-eyed so that the red and green areas overlap (in the lower case, make the crosses merge). The fused colors compete in a patchy, unstable fashion. Some people get glimpses of forbidden reddish green as the patches change color, but the method is much less reliable than using equiluminant stabilized images.

MORE TO EXPLORE

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Perception of Forbidden Colors in Retinally Stabilized Equiluminant Images: An Indication of Softwired Cortical Color Opponency? Vincent A. Billock, Gerald A. Gleason and Brian H. Tsou in *Journal of the Optical Society of America A,* Vol. 18, pages 2398–2403; October 2001.

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JEN CHRISTIANSEN, SOURCE: JEFFERY K. HOVIS *University of Waterloo*

The Prolific Afterlife

On the deep seafloor, the carcasses of the largest mammals give

KEY CONCEPTS

- A single dead whale can nourish a specialized ecosystem that lasts for decades.
- Some signs suggest that whale-fall ecosystems have exchanges with other deep-seafloor communities, such as hydrothermal vents.
- Species similar to those at whale falls may have depended on dead marine reptiles for hundreds of millions of years.

—The Editors

On a routine expedition in 1987, oceanographers in the submersible *Alvin* were mapping the typically barren, nutrient-poor seafloor in the Santa Catalina Basin, off the shore of southern California. On the final dive of the trip, the scanning sonar detected a large object on the seafloor. Piercing through the abyssal darkness down at 1,240 meters, *Alvin*'s headlights revealed a 20-meter-long whale skeleton partly buried in sediment. On reviewing the dive videotapes, expedition leader Craig Smith and his team saw that the skeleton was probably either a blue or a fin whale. The creature appeared to have been dead for years, but the bones and their surroundings teemed with life—wriggling worms, centimeter-size clams, little snails and limpets, and patches of white microbial mats. The skeleton was a thriving oasis in a vast, desertlike expanse.

Almost a year later Smith, an oceanographer at the University of Hawaii at Manoa, returned for a proper study of the skeleton site. His team described several species previously unknown to science, plus some that had been observed only in unusual environments, such as at deep-sea hydrothermal vents.

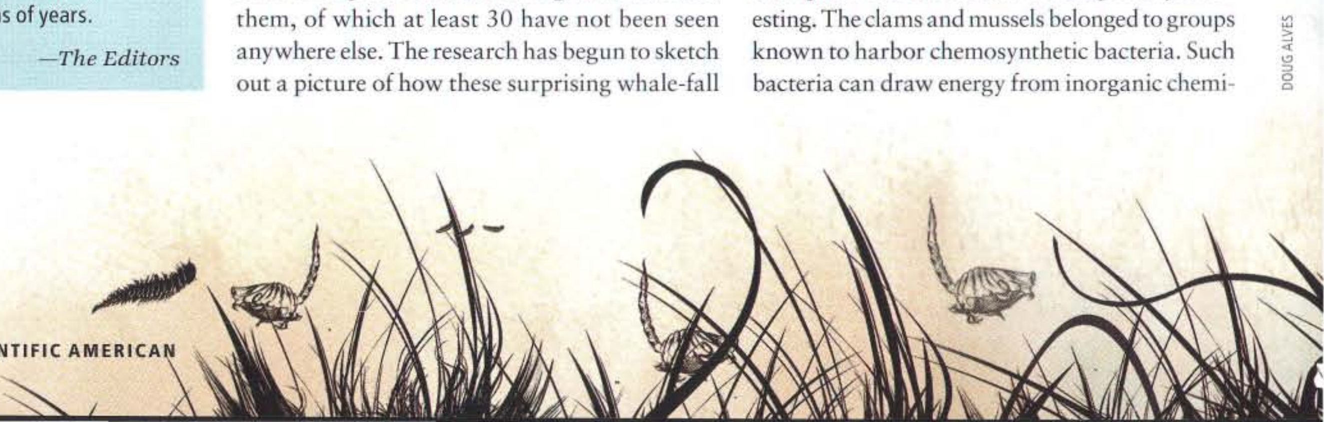
Since then, investigators have documented dozens of communities that are supported by sunken whale carcasses and have described more than 400 species that are living in and around them, of which at least 30 have not been seen anywhere else. The research has begun to sketch out a picture of how these surprising whale-fall communities work and how they have evolved.

The first hint that dead whales could host specialized animal communities came as early as 1854, when a zoologist described a new species of centimeter-size mussel extracted from burrows in floating whale blubber collected off the Cape of Good Hope in South Africa. When industrial deep-sea trawling began in the 20th century, researchers learned that such dependence on dead whales was not a freak occurrence. From the 1960s onward an increasing number of whale skulls and other bones with attached specimens of new mollusk species were recovered from nets around Scotland, Ireland, Iceland and particularly the Chatham Rise to the east of New Zealand. One bone specimen trawled off the South African coast in 1964 was covered with the same small mussel first seen in 1854 in roughly the same area.

Mussels were not the only new animals found in recovered whale bones: a tiny, previously unknown species of limpet—limpets are snail-like mollusks with conical rather than spiral shells—was described in 1985, soon followed by others. The limpets were named *Osteopelta* because of their association with bones.

But not until Smith's fortuitous discovery in 1987 did the full extent of the ecological novelty of sunken dead whales become clear. The mollusk species his team found were especially interesting. The clams and mussels belonged to groups known to harbor chemosynthetic bacteria. Such bacteria can draw energy from inorganic chemi-

DOUG ALVES



of Whales

life to unique ecosystems • By Crispin T. S. Little

cals, and they sometimes form the basis of entire ecosystems. (The earliest organisms, before life "invented" photosynthesis and introduced oxygen into the biosphere, were chemosynthetic, although they had a different metabolism from that of modern chemosynthetic organisms.) Most of the mollusks were known only from other chemosynthesis-based sites: the mussels from sunken wood and hydrothermal vents; vesicomyid clams from vents and cold seeps, where fluids rich in methane and other hydrocarbons leak onto the seafloor; lucinid clams from seeps and anoxic sediments (seafloor sediments lacking oxygen); and a snail from anoxic sediments.

The similarities led Smith and his co-workers to suggest in 1989 that whale skeletons might act as "stepping-stones" for deep-sea animals to spread from one chemosynthetic community to another. Whether creatures can move between communities from one generation to the next or whether species spread on much longer timescales is a question that is still open to this day.

The Making of an Ecosystem

To understand the workings and duration of whale-fall communities, Smith and his colleagues set up a logistically tricky—and somewhat smelly—project in 1992.

They began to take whales that had washed up on the Californian coast and tow them out sea and then sink them in deep waters with up to 2,700 kilograms of steel ballast to counteract the buoyancy of decomposition gases. (Most whales are negatively buoyant when they die and thus sink rather than get beached.) Next they visited the sunken carcasses at regular intervals using *Alvin* or remotely operated vehicles (ROVs). The researchers sank three gray whales over a period of six years and visited these regularly up until 2000. They also revisited the original skeleton found in 1987 and another discovered in 1995.

Whale falls, they observed, go through three partially overlapping ecological stages. The first, which they called the mobile scavenger stage, starts when the whale carcass arrives on the seafloor. Hordes of hagfish tunnel through the meat, while a few sleeper sharks take larger bites. These scavengers strip away the bulk of the whale soft tissue—blubber, muscle and internal organs—and together consume 40 to 60 kilograms a day (the weight of a small person). Even so, the feast can last up to two years, depending on the size of the whale.

The second stage, called the enrichment opportunist stage, lasts up to two years. During this period high-density, though low-diversity, communities of animals colonize the sediments surrounding the whale carcasses and the newly exposed bones. The animals feed directly on the large amounts of blubber and other scraps of nutritious soft tissue left over by the scavengers. This stage is dominated by polychaetes (bristle worms) and crustaceans.

Finally, once the soft tissue is gone, the whale falls enter the third, and longest, phase, known as the sulfophilic stage. Specialized bacteria anaerobically break down lipids contained in the bones. Unlike aerobic bacteria, which would use the molecular oxygen (O_2) dissolved in seawater to digest nutrients, these microorganisms use dissolved sulfate (SO_4) as their source of oxygen and release hydrogen sulfide (H_2S) as waste. Animals cannot use this gas directly as a source of

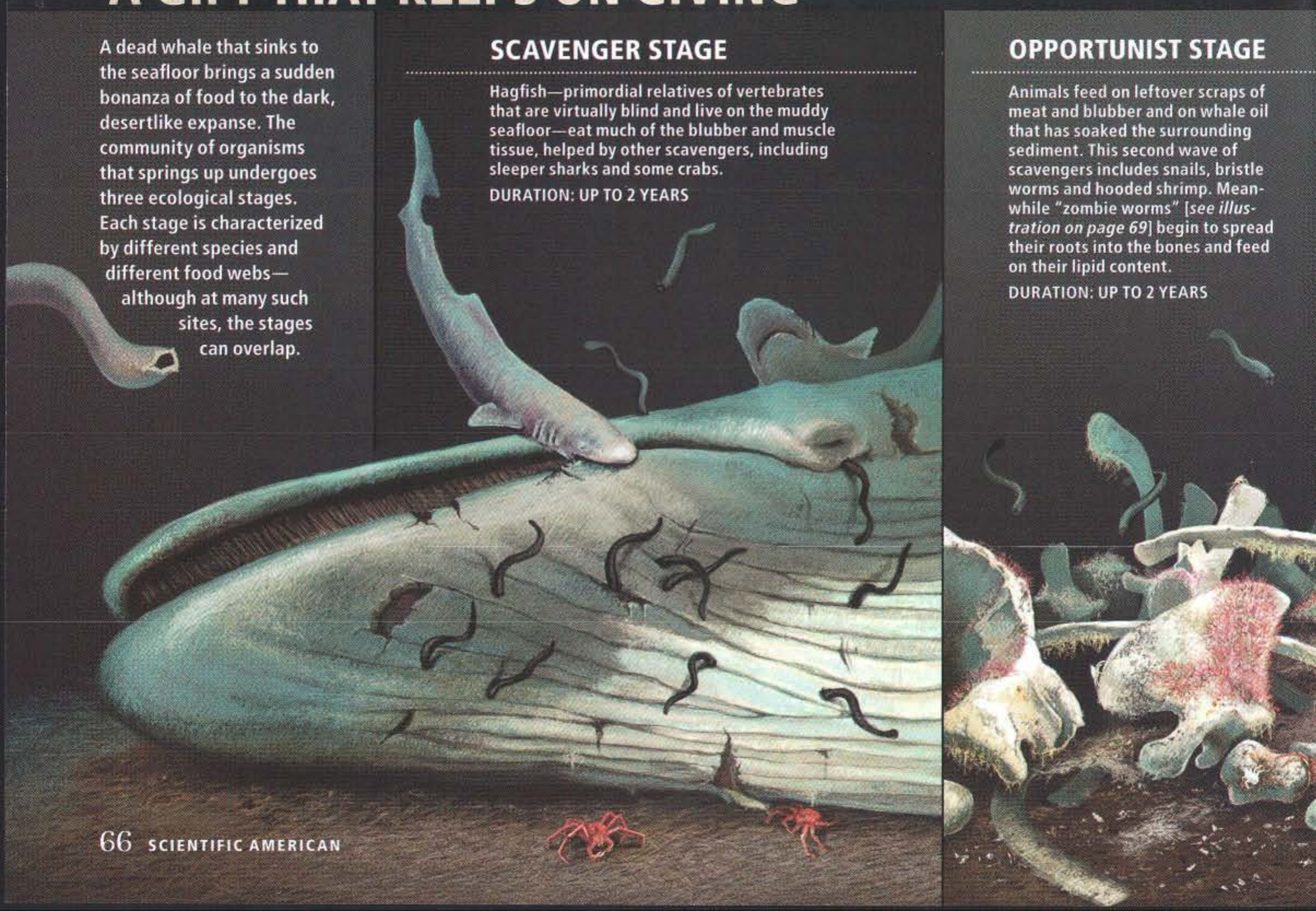
[THE AUTHOR]

Crispin T. S. Little is a senior lecturer in paleontology at the University of Leeds in England. He has been working for the past 14 years on the macroevolutionary history of animal communities found at hydrothermal vents, hydrocarbon seeps and whale falls. On a recent oceanographic cruise he achieved a long-standing personal goal of diving in the *Alvin* submersible to active vents 2.5 kilometers deep on the Pacific seafloor.

COURTESY OF CRISPIN T. S. LITTLE (*Little*); JEN CHRISTIANSEN (*whale-fall illustration*); CATHERINE WILSON (*species inset illustrations*)

[STAGES OF A WHALE-FALL COMMUNITY]

A GIFT THAT KEEPS ON GIVING



A dead whale that sinks to the seafloor brings a sudden bonanza of food to the dark, desertlike expanse. The community of organisms that springs up undergoes three ecological stages. Each stage is characterized by different species and different food webs—although at many such sites, the stages can overlap.

SCAVENGER STAGE

Hagfish—primordial relatives of vertebrates that are virtually blind and live on the muddy seafloor—eat much of the blubber and muscle tissue, helped by other scavengers, including sleeper sharks and some crabs.

DURATION: UP TO 2 YEARS

OPPORTUNIST STAGE

Animals feed on leftover scraps of meat and blubber and on whale oil that has soaked the surrounding sediment. This second wave of scavengers includes snails, bristle worms and hooded shrimp. Meanwhile "zombie worms" [*see illustration on page 69*] begin to spread their roots into the bones and feed on their lipid content.

DURATION: UP TO 2 YEARS

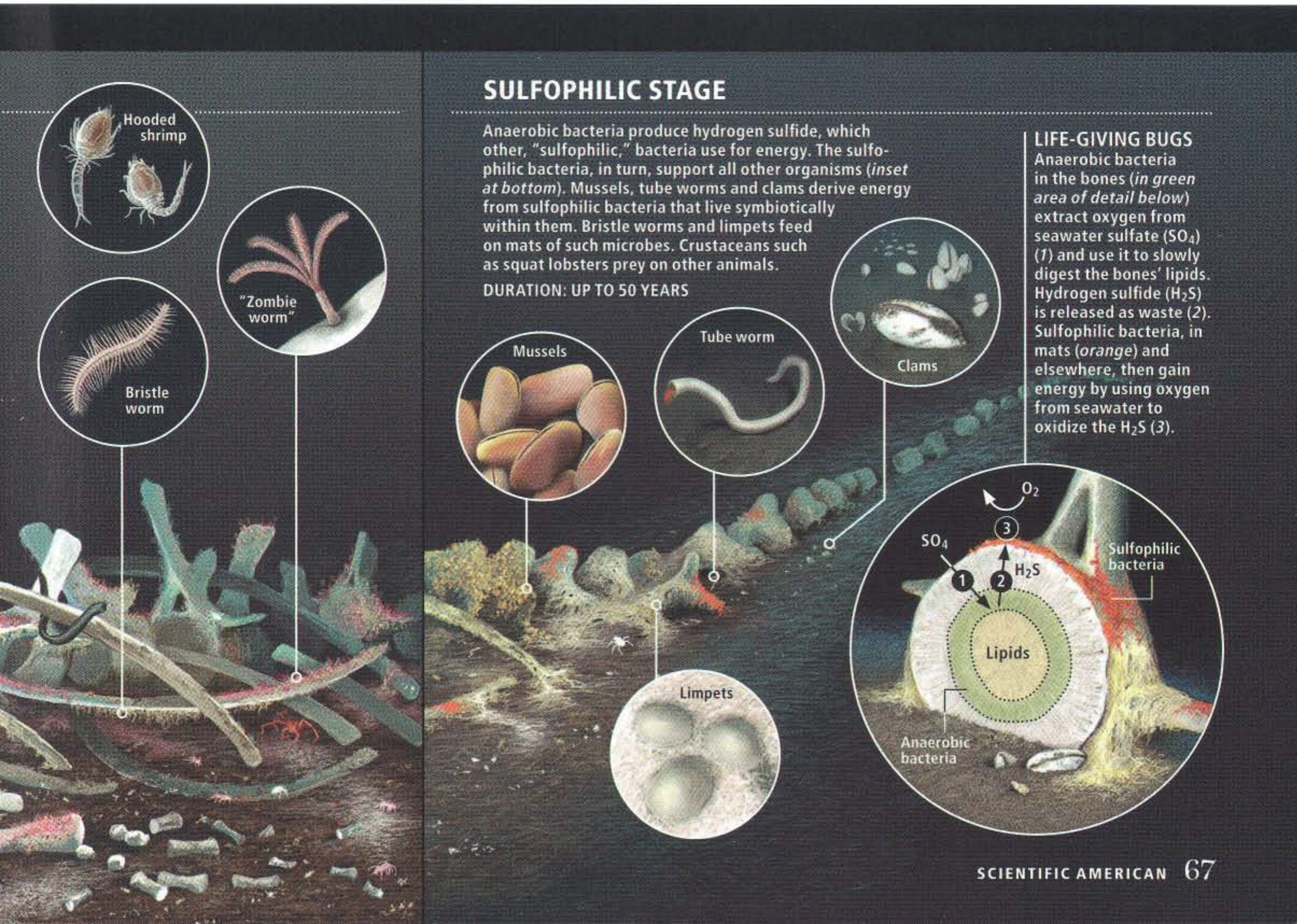
energy, and in fact the gas is typically poisonous to them. But certain chemosynthetic bacteria can. They take O_2 from the seawater to oxidize the sulfide, generating energy for growth. Animals can then either exploit such bacteria symbiotically (as do mussels and vesicomyid and lucinid clams) or feed on them by grazing bacterial mats (as do limpets and snails). For reasons that are not yet well understood, whale bones are extremely rich in lipids—a 40-ton whale carcass may contain 2,000 to 3,000 kilograms—and their decomposition is a slow process. As a consequence, for a large whale the sulfophilic stage can last up to 50 years, even perhaps a century.

Using these data—together with their estimate that around 69,000 great whales die every year—Smith and his co-workers guessed that there might be 690,000 skeletons of the nine largest whale species rotting in the world's oceans at any one time. (Of course, before industrial whaling caused a dramatic crash in large-whale populations during the past two centuries, considerably more whale falls would have been active, perhaps as many as six times more.) The average distance from one whale to the next would then be just 12 kilometers; along the migration route of gray whales, the average distance may be as short as five kilometers. Such spacing may be close enough for larvae to disperse from one site to another, which the team saw as further support for their stepping-stone model for the dispersal of chemosynthetic organisms between whale falls, hydrothermal vents and cold seeps.

Night Creatures Calling

Ever since Smith and his colleagues set up their whale-fall experiment, sinking large dead whales has proved quite popular; three other groups, based in Sweden, Japan and Monterey, Calif., have been conducting similar experiments. Other whale skeletons have been found by chance in various deep-water sites, for example, at the Torishima Seamount south of Japan and in Monterey Bay. The newer studies have confirmed that a consistent group of organisms depends on whale falls throughout the world's oceans. But the stag-

There may be 690,000 skeletons of the nine largest whale species rotting in the world's oceans at any one time.



SULFOPHILIC STAGE

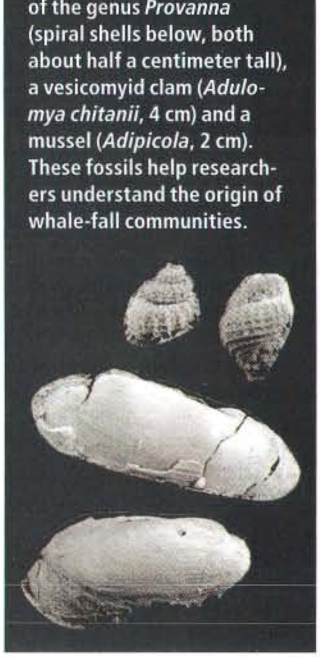
Anaerobic bacteria produce hydrogen sulfide, which other, "sulfophilic," bacteria use for energy. The sulfophilic bacteria, in turn, support all other organisms (*inset at bottom*). Mussels, tube worms and clams derive energy from sulfophilic bacteria that live symbiotically within them. Bristle worms and limpets feed on mats of such microbes. Crustaceans such as squat lobsters prey on other animals.

DURATION: UP TO 50 YEARS

LIFE-GIVING BUGS
Anaerobic bacteria in the bones (*in green area of detail below*) extract oxygen from seawater sulfate (SO_4) (*1*) and use it to slowly digest the bones' lipids. Hydrogen sulfide (H_2S) is released as waste (*2*). Sulfophilic bacteria, in mats (*orange*) and elsewhere, then gain energy by using oxygen from seawater to oxidize the H_2S (*3*).

FOSSIL RELATIVES

Various fossil whales show signs of having sustained communities similar to those of modern whale falls—including many of the invertebrates that depend on symbiotic sulfide-oxidizing bacteria. One specimen from Middle Miocene (about 12 million years ago) rocks on Hokkaido Island, Japan, was surrounded by several shells of mollusks, including snails of the genus *Provanna* (spiral shells below, both about half a centimeter tall), a vesicomyid clam (*Adulomya chitanii*, 4 cm) and a mussel (*Adipicola*, 2 cm). These fossils help researchers understand the origin of whale-fall communities.



es seen in the Santa Catalina skeletons are not as apparent elsewhere.

One reason for the discrepancy may be that the experimental sites selected by the Smith team are relatively oxygen-poor, leading to reduced decomposition rates. Another reason might be the activities of the extraordinary worm *Osedax* (Latin for "bone devourer"), also known as the zombie worm. This small animal—one centimeter or less in length—was first described in 2004 from a Monterey Bay whale and later found at the experimental sites in Sweden and Japan. Still later, researchers found the worm at the southern Californian whale falls as well—where at first it had been overlooked—but in smaller numbers.

Osedax has little appendages that stick out into the water column for gas exchange but can be retracted into a mucous tube if disturbed. The animal then looks like a blob of mucus adhering to the bone surface. Just like certain intestinal parasites, *Osedax* has no digestive tract at all as an adult—no mouth, stomach or anus. But uniquely, it uses green, fleshy "roots" to tunnel into exposed whale bones, presumably to obtain lipids or proteins, or both, for symbiotic bacteria contained within its roots. (The worm's reproductive strategy is also unusual. All adults are female, but each carries in its body dozens of tiny males that never pass the larval stage—and whose only role, it seems, is to produce sperm.)

Osedax is closely related to the giant tube worms that live at many vent and seep communities. Genetic evidence suggests that it is around 40 million years old, about the same age as vesicomyid clams and whales.

The tunneling activity of *Osedax* rapidly destroys the exposed whale bones, which likely speeds up the sulfophilic stage for an infested skeleton, thus affecting its entire habitat. The finding could mean that many whale falls are active on the seafloor for less time than was originally thought. This time reduction poses a challenge to the stepping-stone hypothesis, because fewer active whale falls should make it more difficult for animals (or their larvae) to get from one chemosynthetic site to another.

Bones of Contention

Whereas vents and cold seeps have been around since the early earth—and vents in particular may be where life got started in the first place—the appearance of whales is, of course, relatively recent. A natural question is when and how have ecosystems evolved that seem to depend on whale carcasses for their existence, which in turn should help clarify their connection to other deep-sea communities. The obvious place to look is in the fossil record.

Although many fossil whales have been found over the past 150 years, it was only in 1992 that the first ancient whale-fall communities were recognized, in Washington State rocks from the Oligocene (34 million to 23 million years ago). Intense interest in these bizarre communities has since turned up more examples. Among them are some fossils from the Miocene (23 million to five million years ago) found in California and in three sites in Japan—including two that I have worked on with my colleague Kazutaka Amano of the Joetsu University of Education. All these ancient whale-fall communities are recognized as such by the presence of mollusk fossils belonging to groups that host chemosynthetic bacteria or graze on microbial mats at chemosynthetic sites. As might be expected, the fossil record of whale-fall assemblages contains no remains of

FROM "A NEW MIOCENE WHALE-FALL COMMUNITY FROM JAPAN," BY KAZUTAKA AMANO, CRISPIN T. S. LITTLE AND KIYOKAZU INOUE, IN *PALAEOGEOGRAPHY, PALAEOCLIMATOLOGY, PALAEOECOLOGY*, VOL. 247, ISSUES 3-4; APRIL 30, 2007 (*fossils*); COURTESY OF MBARI (*whale fall*)

LYING 2,891 METERS DEEP in Monterey Bay, Calif., this 10-meter-long gray whale provides nourishment for a thriving community, including scavenging sea cucumbers (*Scotoplanes globosa*, crawling on foreground) and bone-eating worms (*Osedax rubiplumus*, on bones). The three shots that make up this montage were taken in 2002; some of the bones seen here have since completely decomposed.

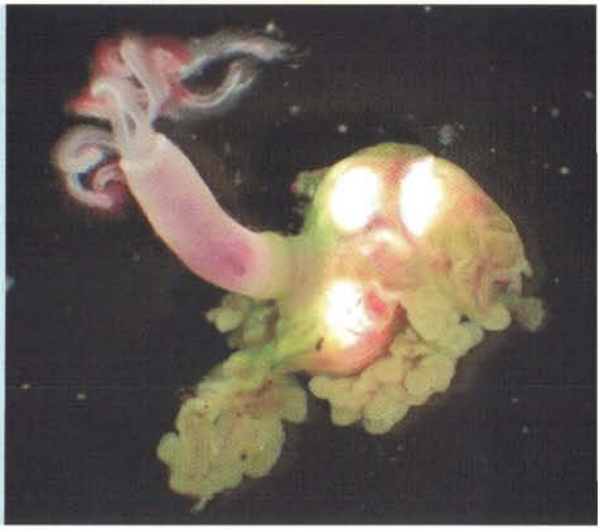
soft-bodied animals such as worms, because soft body parts decay readily. So no one knows yet whether worms such as *Osedax* lived there.

In 2006 Steffen Kiel, then at the University of Leeds in England, and Jim Goedert of Seattle's Burke Museum of Natural History and Culture pointed out that the earliest whale-fall communities from the late Eocene and the Oligocene were dominated by clams that also occur in nonchemosynthetic habitats; the chemosynthetic mollusks that characterize modern whale falls in the sulfophilic stage do not show up until the Miocene fossils. The researchers concluded that the early whales were not yet large enough to host sulfophilic communities. Recently, however, a small Miocene whale skeleton was found in cliffs on a Californian island that had associated vesicomyid clams. This discovery suggests that it is not so much a whale's size that matters to the chemosynthetic mollusks. Instead the relative lipid content in whale bones probably increased over the past 20 million years or so, perhaps because it enhanced survival as whales moved into open-ocean environments.

In fact, ever since the discovery of whale-fall communities, researchers have suspected that similar communities may have existed even earlier than the first whales, in the sunken carcasses of ancient marine reptiles, among them plesiosaurs, ichthyosaurs and mosasaurs. These reptiles were among the dominant predators of the Mesozoic oceans. (The Mesozoic, the geologic era that stretches from 251 million to 65 million years ago, comprises the Triassic, the Jurassic and the Cretaceous and thus the entire time when the dinosaurs ruled on land.) This idea received a strong boost in 1994 with the description of a single fossil specimen of the limpet *Osteopelta* from a turtle bone in Eocene sediments from New Zealand. Although the Eocene is more recent than the Mesozoic, the discovery demonstrated that whale-fall limpets were also able to live on reptile bones and thus perhaps on the extinct Mesozoic marine reptiles as well.

Then, in 2008, a research group from Japan and Poland reported the discovery of bones of two plesiosaur skeletons originally around 10 meters long with associated provannid snail specimens from upper Cretaceous rocks in Japan. Because provannids are only known from chemosynthetic sites, the scientists suggested that the sunken plesiosaurs were able to support a community comparable to the sulfophilic stage of modern whale falls. But these reptiles went extinct 65 million years ago along with the dinosaurs. That is more than 20 million years before whales evolved, suggesting that there may have been a repeated evolution of specialized communities of animals dependent on large vertebrate carcasses sinking to the seafloor.

ZOMBIE WORMS, also known as *Osedax* (Latin for "bone devourer"), grow "roots" in dead whale bones, which they slowly consume. The worms seem to live exclusively at whale falls. This *Osedax frankpressi* has been removed from a whale bone to show its root system (*green*) and ovaries (*white*); typically only the one-centimeter-long body (*pink*) and its plumes would be visible. At least five different species of *Osedax* have been discovered so far.



COURTESY OF MBARI

The Japanese and Polish group showed convincingly that the plesiosaur bones looked internally very like modern whale bones, with lots of marrow space that would have contained lipids in life. Whether the bones were in fact rich in lipids will not be easy to determine, however. On the other hand, it seems that many groups of animals present in whale-fall sulfophilic communities were already present in seep, wood-fall and probably vent communities and that they avidly exploited the newly evolved chemosynthetic habitat when whales evolved.

The fossil record of whale falls remains rather scant, with data coming almost exclusively from Japan and the Western coast of the U.S. Fossil evidence of *Osedax* could be especially helpful, given the organism's unique ability to shape the modern communities. Although the lack of a skeleton makes it unlikely that direct evidence of the worm will be found, the borings it makes in whale bones may be recorded in fossils, and many investigative groups are actively searching for them.

The global distribution of modern whale-fall communities is also still poorly characterized. So far only a few whale carcasses have been found, and we know nothing about several areas that have large whale populations, such as Antarctica and the Southern Ocean. More finds, both active and fossil, will be necessary to reveal whether the ecology and evolutionary history of whale falls are truly linked to those of reptile falls and how both types of ecosystems relate to the other deep-sea chemosynthetic communities. ■

➡ MORE TO EXPLORE

The Mammals That Conquered the Seas. Kate Wong in *Scientific American*, Vol. 286, No. 5, pages 52–61; May 2002.

Ecology of Whale Falls at the Deep-Sea Floor. Craig R. Smith and Amy R. Baco in *Oceanography and Marine Biology: An Annual Review*, Vol. 41, pages 311–354; 2003.

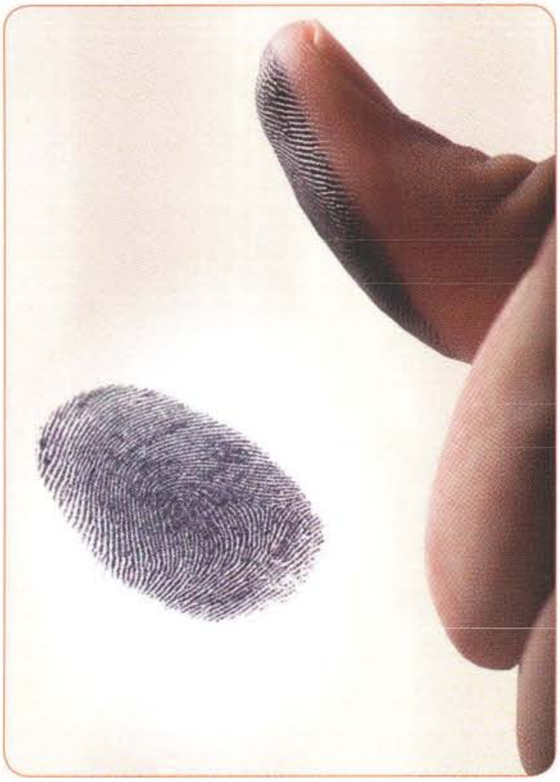
Expanding the Limits of Life. Alexander S. Bradley in *Scientific American*, Vol. 301, No. 6, pages 38–43; December 2009.

Q Can people ever lose their fingerprints?

Science writer **Katherine Harmon** interviewed experts to hand over the answer:

Fingerprints can indeed be removed, both intentionally and unintentionally. The May 2009 issue of the *Annals of Oncology* reported (online) a striking example of the latter case: a 62-year-old man from Singapore was detained while traveling to the U.S. because a routine fingerprint scan showed that he actually had none.

The man, identified only as Mr. S, had been taking the chemotherapy drug capecitabine (brand name Xeloda) to keep head and neck cancer in check. The medication gave him a moderate case of hand-foot syndrome (also called chemotherapy-induced acral erythema), which can cause swelling, pain and peeling on the palms and soles of the feet—and, apparently, loss of fingerprints. Mr. S, who was freed when officials decided he was not a security risk, says he had not noticed that his fingerprints had vanished before he set out on his trip. After the incident, Mr. S's physician, who authored the paper, found informal online mentions of other chemo patients complaining of lost fingerprints.



Edward P. Richards, director of the Program in Law, Science and Public Health at Louisiana State University, says that other diseases, rashes and the like can have the same effect. "Just a good case of poison ivy would do it." But he observes that "left alone, your skin replaces at a fairly good rate, so unless you've done permanent damage to the tissue, it will regenerate."

Kasey Wertheim, who is president of Complete Consultants Worldwide and has done forensic and biometric work for the U.S. Department of Defense and Lockheed Martin, says that the people who most often lose their fingerprints seem to be bricklayers, who wear down print ridges handling rough, heavy materials, as well as "people who work with lime [calcium oxide], because it's really basic and dissolves the layers of the skin." Secretaries may also have their prints obliterated, he adds, "because they deal with paper all day. The constant handling of paper tends to wear down the ridge detail."

"Also," Wertheim, notes, "the elasticity of skin decreases with age, so a lot of senior citizens have prints that are difficult to capture. The ridges get thicker; the height between the top of the ridge and the bottom of the furrow gets narrow, so there's less prominence." Burning—with heat or chemicals—can blot out fingerprints as well, but then the resulting scars can become a unique identifier.

Wertheim says that many cases of intentional fingerprint mutilation have been documented. Usually in these instances, people damage the layer of skin that forms the "template" for the fingerprint and the epidermis at the surface.

The first case of documented fingerprint mutilation, he points out, was back in 1934, by Theodore "Handsome Jack" Klutas, who was head of a gang known as the College Kidnappers. "When the police finally caught up with him, Klutas went for his gun, and the police returned fire, killing him," Wertheim recounts. "When they compared his postmortem fingerprints, police found that each of his prints had been cut by a knife, resulting in semicircular scars around each fingerprint. Although he was glorified in the media, it was an amateur job; the procedure left more than enough ridge detail to identify him." ■

DO YOU HAVE A QUESTION?
Please send it to us at experts@SciAm.com

SETH JOEL *Getty Images*

The Agenda Setters

Bringing Science to Life

Meet The Future

California Academy of Sciences | San Francisco | November 18, 2009

SCIENTIFIC AMERICAN partnered with The California Academy of Sciences to present a live discussion with technology editor Michael Moyer based on our December *World Changing Ideas* cover story.

Decade2 Education

Ronald Reagan Building | Washington D.C. | December 8, 2009

Our first program in the *Decade2* series explores our most pressing challenges of education innovation. Some of the best minds on the subject included Deputy Secretary of Education Tony Miller, Undersecretary of Energy Kristina Johnson and Joe Miletich Sr. VP, Research & Development at Amgen, the sponsor of this event.

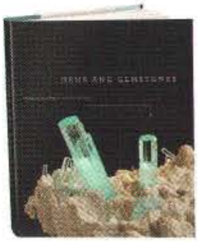
The Science of Bling ▪ Time Theory ▪ Youthful Aging

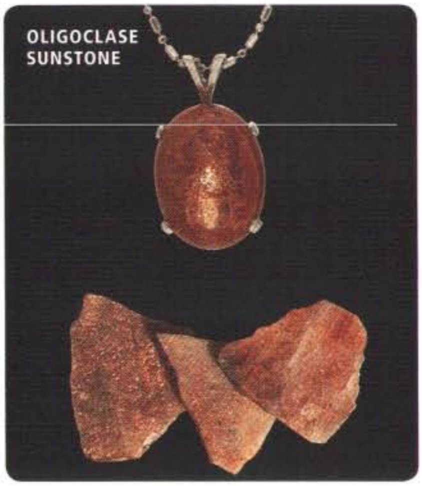
BY KATE WONG

GEMS AND GEMSTONES

by Lance Grande and Allison Augustyn. University of Chicago Press, 2009 ($45)

Eye candy abounds in this volume on gems based on the newly revamped Grainger Hall of Gems at the Field Museum in Chicago. The book covers such topics as how gems form in nature, how they are classified, and the fascinating history of humanity's love of jewels.

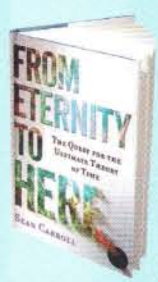




EXCERPT

FROM ETERNITY TO HERE: THE QUEST FOR THE ULTIMATE THEORY OF TIME

by Sean Carroll. Dutton, 2010 ($26.95)



In his first popular science book, theoretical physicist Sean Carroll tackles nothing less than the nature of time. Along the way he explains why the past is different from the future—and what this reveals about the beginning of the universe.

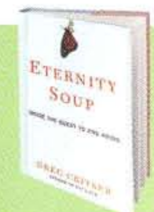
"What does it mean to say that time has a direction, an arrow pointing from the past to the future? Think about watching a movie played in reverse. Generally, it's pretty clear if we are seeing something running the 'wrong way' in time. A classic example is a diver and a pool. If the diver dives, and then there is a big splash, followed by waves bouncing around in the water, all is normal. But if we see a pool that starts with waves, which collect into a big splash, in the process lifting a diver up onto the board and becoming perfectly calm, we know something is up....

"Certain events in the real world always happen in the same order. It's dive, splash, waves; never waves, splash, spit out a diver. Take milk and mix it into a cup of black coffee; never take coffee with milk and separate the two liquids. Sequences of this sort are called irreversible processes....

"Irreversible processes are at the heart of the arrow of time. Events happen in some sequences, and not in others. Furthermore, this ordering is perfectly consistent, as far as we know, throughout the observable universe. Someday we might find a planet in a distant solar system that contains intelligent life; but nobody suspects that we will find a planet on which the aliens regularly separate (the indigenous equivalents of) milk and coffee with a few casual swirls of a spoon. Why isn't that surprising? It's a big universe out there; things might very well happen in all sorts of sequences. But they don't. For certain kinds of processes—roughly speaking, complicated actions with lots of individual moving parts—there seems to be an allowed order that is somehow built into the very fabric of the world."

ALSO NOTABLE

BOOKS



- **Eternity Soup: Inside the Quest to End Aging** by Greg Critser. Harmony, 2010 ($26)
- **Water: The Epic Struggle for Wealth, Power, and Civilization** by Steven Solomon. HarperCollins, 2010 ($27.99)
- **The Humans Who Went Extinct: Why Neanderthals Died Out and We Survived** by Clive Finlayson. Oxford University Press, 2009 ($29.95)
- **Lake Views: This World and the Universe** by Steven Weinberg. Harvard University Press, 2010 ($25.95)
- **Sexy Orchids Make Lousy Lovers: & Other Unusual Relationships** by Marty Crump. University of Chicago Press, 2009 ($25)
- **Priceless: The Myth of Fair Value (and How to Take Advantage of It)** by William Poundstone. Hill and Wang, 2010 ($26.99)
- **The Big Questions: Tackling the Problems of Philosophy with Ideas from Mathematics, Economics, and Physics** by Steven E. Landsburg. Free Press, 2009 ($26)
- **The Language of Life: DNA and the Revolution in Personalized Medicine** by Francis S. Collins. HarperCollins, 2010 ($26.99)
- **The Other Brain: From Dementia to Schizophrenia, How New Discoveries about the Brain Are Revolutionizing Medicine and Science** by R. Douglas Fields. Simon & Schuster, 2010 ($27)
- **Storms of My Grandchildren: The Truth about the Coming Climate Catastrophe and Our Last Chance to Save Humanity** by James Hansen. Bloomsbury, 2009 ($25)

FOLKS WE FOLLOW ON TWITTER

- **Karen James, geneticist at the Natural History Museum in London (@kejames)**
- **Gary Schwitzer, publisher of HealthNews Review.org (@garyschwitzer)**
- **Brian Switek, science writer with a focus on evolution (@Laelaps)**
- **Mike Brown, planet hunter at the California Institute of Technology (@plutokiller)**
- **Kevin Pho, physician and blogger (@kevinmd)**

COURTESY OF JOHN WEINSTEIN AND LANCE GRANDE

Greenhouse Bananas

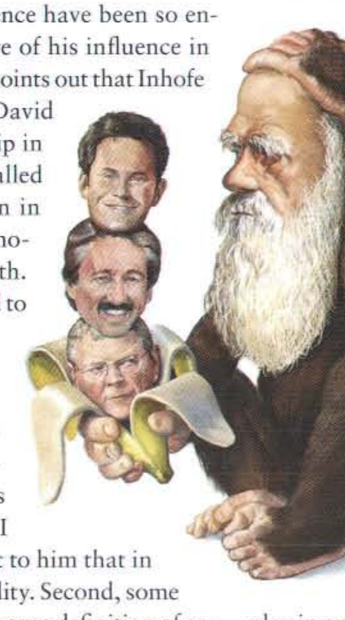
Two men tout stuff you didn't learn in school, if you went to a good school

BY STEVE MIRSKY

Here's my conclusion: the only strong evidence we have that Oklahoma Senator James M. Inhofe isn't a clown is that his car isn't small enough. As I write in early December, the Copenhagen climate change conference has just begun. And Inhofe, that gleeful anarchist, says he is going to Copenhagen to try to sabotage the affair.

Inhofe has famously called climate change "the greatest hoax ever perpetrated on the American people." (Actually, the greatest hoax ever perpetrated on the *American* people was Lord Amherst's distribution of smallpox-ridden blankets, but I digress.) But he has also called global warming the "second largest hoax ever played on the American people after the separation of church and state." Well, it's good to know that the senator is capable of revising his theories after he acquires new information, a necessary condition for a truly scientific worldview.

Inhofe's attacks on climate change science have been so engrossing that until recently I was unaware of his influence in Uganda. Investigative reporter Jeff Sharlet points out that Inhofe influences Ugandan parliament member David Bahati through their common membership in the Washington, D.C. evangelical group called the Family. Bahati introduced legislation in Uganda that recognized "aggravated homosexuality," punishable in some cases by death. (Scrutiny by MSNBC's Rachel Maddow led to Inhofe repudiating the bill as this issue went to press.)



"Aggravated homosexuality" ranges from being infected with HIV to failing to report a homosexual to authorities to supporting same-sex marriage. Passage of this bill would thus mean two things. First, I would have to call my father and come out to him that in Uganda I engage in aggravated homosexuality. Second, some gay friends of mine will have to change their own definition of aggravated homosexuality, which currently means having trouble getting Lady Gaga tickets.

Inhofe himself is so intolerant that he once proclaimed, "I'm really proud to say that in the recorded history of our family, we've never had a divorce or any kind of homosexual relationship." Based on statistics, I'm betting that the Inhofes will welcome a homosexual to the family in the near future or that the senator's use of the word "recorded" was strategic.

(And if I ever hear any of his family singing show tunes from the great American musical named for the state the senator represents, I'm calling the cop in the Village People to make an arrest. The charge: fabulousness.)

Inhofe may subscribe to the unscientific young earth view of creation, which puts the age of our planet at about 10,000 years. I called and wrote his office in 2008 to find out his belief about the earth's age, as I suspected it might inform his views on climate and fossil fuels. After almost a year, I got an information-free reply, thanking me for my interest.

Which brings me to young earth creationist Ray Comfort. He's the antievolution activist who, along with former child sitcom star Kirk Cameron, recently passed out copies of *On the Origin of Species* with a new introduction that in effect explains how Charles Darwin was wrong, a bigot, a misogynist, Hitler's dad, a cribbage cheat and the true kidnapper of the Lindbergh baby.

Comfort himself has been accused of cribbing parts of that intro from the writings of University of Tennessee lecturer Stan Guffey, who told the *Knoxville Metro Pulse*: "[Comfort's] introduction begins with a nice, sweet little biography, then degenerates into intellectually lame, lazy distortions, selective reading of the literature, picking and choosing of facts, and misreadings of the historical record.... [He] gently moves folks into the notion that they don't want to read what comes after the introduction. He just wants his 50 pages read, 47 of which are anti-intellectual, dishonest drivel, the first three of which are pretty good because I wrote them."

Comfort's academic rigor is also on display in an infamous YouTube video in which he shows Cameron how the banana is concrete evidence for divine creation: the hand-friendly structure of the banana, with its peel packaging, includes ridges allegedly corresponding to the grooves where our fingers flex. (Alert the Nobel committee.) I'm waiting for the video where Comfort talks about the coconut, that nutritious seed clearly designed by God to be opened with an entire Sears Craftsman tool set. Which could also be used to start whittling Inhofe's gas guzzler down to more traditional circus car proportions. ■

PHOTOGRAPH BY FLYNN LARSEN; ILLUSTRATION BY MATT COLLINS